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Hazard-Rating Systems in Forest Insect Pest Management:

Symposium Proceedings

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and
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School of Forest Resources
Center for Continuing Education

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FOREWORD

Recent interest in rating forest stand susceptibility to insect damage prompted the organization of this symposium on hazard-rating systems in forest pest management. The theme of the symposium was the development and use of stand susceptibility rating systems for insect pests of North American forests. The aims of the symposium were (1) to identify hazard- and risk-rating methods in use in North America and to discuss land managers' experience with them; (2) to investigate methods for developing, validating, and implementing rating systems; and (3) to identify where additional needs exist to improve the utility of rating systems. How well these goals have been accomplished can be judged from the papers included in these Proceedings.

The symposium was a cooperative effort between the Society of American Foresters' Entomology Working Group, the USDA Forest Service, and the University of Georgia. Members of the organizing committee were

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The organizing committee would like to acknowledge the assistance of the USDA Forest Service's IPM Bark Beetle Program in the preparation of the Symposium Proceedings, especially the editorial and organizational skills of Janet Searcy, Program Writer/Editor.

Roy L. Hedden
Program Chairman

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MANAGING FOREST PESTS--CHALLENGES OF THE 1980's

Fred B. Knight[1]

I appreciate the opportunity to present the lead paper in this symposium on hazard-rating systems; thank you to the planning committee for the invitation. In thinking about material to discuss, I spent more time trying to decide on what to cover than on writing because of the temptation to spend time on historical information or on discussion of specific hazard-rating problems. These will be thoroughly covered by the presentations to follow during the next 2 days; thus I have tried to avoid duplication.

I have decided to discuss some of the related questions on resource management that often have more impact on what we do about forest insect problems than our well-prepared integrated pest management (IPM) schemes or our thoroughly analyzed hazard-rating systems. These will be presented as a series of questions for which I have no clear answers. I am convinced that hazard ratings are extremely important, that valid decisions on pest management of many species cannot be made without some form of hazard evaluation, and that these evaluations should be readily understood by resource managers. However, there is a vast distance between known need and actual application in the woods.

WHY DON'T PEOPLE READ THE LITERATURE?

During a 1974 symposium (Chansler 1976), Lester W. Hazelton of Great Northern Paper Co. made the following comments about the spruce budworm *(Choristoneura fumiferana)*, which killed so many trees during the outbreak ending in the 1920's.

> After 1920, cutting rates were rapidly reduced as merchantable and salvageable timber became unavailable. The low point in the harvest period was in 1924, when only 31,000 cords were cut on company lands. The annual cut for the next 10 years was only 44,000 cords per year on 1,500,000 acres of timberland, or an annual rate of only 0.03 cords per acre. Wood procurement to the mills averaged over 300,000 cords annually.

Later he remarked that "the structure and long-term impact of this last major budworm attack should certainly make us aware of future probabilities."

Despite this material published for all to see, I still hear comments from professional resource people that we have no real knowledge of the impact of the last outbreak of the budworm. People just do not read what has been published. If that statement seems too strong, the alternative is that even when the reading has been done, we are unable to retain enough to remain well informed.

We have help for this situation in general summaries of forest insect problems (Baker 1972, Furniss and Carolin 1977) and more thorough monographs or compendia on specific problems (Kibbee et al. 1978, Brookes et al. 1978, Miller and Keen 1960). These may be valuable sources for professionals but not if they merely fill space on the library shelf. The literature is becoming so large that we just don't seem to cope with it. I have been recently involved in a literature review on the spruce budworms. We issued our first publication of abstracts covering 1,533 citations (Jennings et al.) in 1979; some of you have seen it. Since then we have deposited some 600 additional citations and abstracts into computer storage at Oak Ridge and have well over a thousand more in process. Interestingly, I have heard some individuals in Maine say (within the past 5 years) that little is known about the spruce budworm.

Part of the problem may be related to the location of the literature in obscure publications or journals not readily available to everyone. But that is not the whole story, as we know that a person can obtain plenty of information on most problems. I have confined my journal references in this article to the "Journal of Forestry" to illustrate the diversity of material available to the professional forester in his/her own publication. People have simply not been trained to read and to seek information. It is much simpler to complain or to state emphatically that nothing is known. We have a great need for persons interested and capable in the technology transfer area because we must bring to the attention of managers more of the information we have ready to use.

HAVE PEOPLE READILY ACCEPTED PREVENTIVE METHODS FOR MANAGING PEST PROBLEMS?

This leading question is one that we all know has a simple answer. No, land owners do not readily accept a preventive method. Why? Because applications of

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such methods are not cheap and the general attitude has questioned why anyone should spend money when no damage is apparent.

I believe our plantations have provided some of the more dramatic examples of this problem. The difficulty arises from an unwarranted assumption on the part of owners and managers that has been very difficult to overcome. People assume that after planting trees nothing needs to be done until the first thinning, if then. The usual plan, if one exists, calls for doing something about insects only after a real emergency arrives. Thus an expenditure for pest management usually is not planned: it is an extra cost to be avoided. A good forest management plan should call for an opposite approach in which a planned expenditure is budgeted not only for site preparation and planting but also for other needs including insect control prior to the first thinning. Such a radical approach seems out of the question to most managers even though the cost is rather small compared to site preparation and planting.

We resource managers (foresters) take much pride in the idea that among all conservationists we are the best of the long-term planners. But we also seem to apply an excessively short-range view to the expressed need for providing a system of "affordable forestry" (Slocum 1979). We have failed to understand what Slocum suggests: by more planning and a little extra thinking, we can accomplish much more with less money in the woodlot management area. The point I am making is that preventive methods may be cheaper in the long run than direct control in the management of plantation pest problems. The problem is to get the owner and manager to spend some time on planning.

One reason why preventive methods have not been adopted relates to markets and wood availability. Prevention is a common practice for insect management in countries where intensive forest management is practiced on most acres. In such localities the value of the forest has increased greatly and most of the wood grown is badly needed. Simply, the land manager cannot risk losing the valuable trees.

We may have expected too much in the past, but we have reached the stage in most sections of this country where there is no large surplus of timber available to replace losses. Thus, we should be applying preventive measures similar to those utilized in countries where intensive management is common. We don't react quickly enough to change in management intensity and we are not getting people trained to do the necessary planning. We seem to operate with a malaise similar to that in the automobile industry. The principles of planning and discussion of alternative strategies should be a part of most forestry courses so that professionals, at least, will be willing and eager to adapt as conditions change.

Prevention is often just good silviculture as we have repeatedly seen in practice or in natural occurrences. Wickman's (1980) article on the increased growth of white fir following an outbreak of Douglas-fir tussock moth *(Orgyia pseudotsugata)* is an example of a natural occurrence operating as a stimulant to growth (fig. 1). He concluded that the increased growth was likely due to the thinning effect of tree mortality.

Figure 1.--Could thinning applied earlier have prevented some of these losses caused by the Douglas-fir tussock moth? (USDA Forest Service.)

ARE WE REALLY ACCOMPLISHING MORE THROUGH INTEGRATED PEST MANAGEMENT?

I would like to give a very positive yes answer to this question but can manage only a very weak positive response. But very positive results have accrued from the discussions and the publicity resulting from the adoption of the terminology for this evolving process. The proof of real accomplishment is not obtained by reciting population numbers or presenting new models of how a pest may function or

by showing that both chemical and biological methods were used on some project. Proof of accomplishment comes when we show reduced losses in the forest along with fewer environmental impacts; this may be relatively easy to present in theory but is often very difficult to show in the forest.

Stark (1977) presented some ideas about IPM in relation to forest resources. He emphasized the ecosystem concept and the need for an understanding of both economic and social values. Stark pointed out that the most appropriate methods for working with IPM are those developed through the systems analysis process. Such results will be valid if the data utilized are accurate expressions of the ecological, economic, and social impacts of any management manipulations applied to the problem.

Actual accomplishment falls far short of the stated goals, and some of the liturgy of our professional people has served to confuse many persons. "Management" suggests to many that something of value is being managed; thus the idea of managing pests is difficult to swallow. Then when it is explained that we really aren't so much concerned with the pest as we are with the forest, people wonder why we don't say so to start. Somehow the whole idea has been turned around, and we talk of ecosystems as a part of pest management rather than pests as a part of ecosystem (forest) management.

Control work on the eastern spruce budworm (fig. 2) has recently led to an emphasis on integrated management for that pest. Irland (1977) described the planned program as relying on silviculture, salvage, research, and improved insecticides. In 1944 Westveld suggested that an action program against the budworm should involve application of (1) biological control, (2) control with insecticides, and (3) control through forest management. The principles cited are similar, though the likelihood of accomplishment in 1980 is greater than in 1944 because of present-day market conditions and the availability of new techniques.

Control projects covering a million acres or more seem to be accomplishing little that is different in 1980 from similar applications in 1950. The major new developments on these projects are the use of chemical materials with fewer side effects that must pass through strict registration requirements. This is not proof of IPM.

We will succeed if we convince forest managers and professional foresters that pest problems are an integral part of the forest management process. When we have developed a feeling among professional foresters that the handling of pest problems is as important to success in resource management as are fire control, thinning practices, harvesting, etc., we will have an opportunity to reach our goals. We have much to do to achieve any real change in attitudes about forest entomology and pest management in general. We still move from one outbreak to the next, practicing IPM where the methods may be least likely to succeed.

Figure 2.--Is integrated pest management the answer to the eastern spruce budworm problem or should we emphasize better management of the spruce-fir forest type? (Photo by M. W. Houseweart.)

Do we really want to manage the spruce budworm or are we really interested in better management of the spruce-fir forests? The question seems appropriate at this point because we know that if methods are developed as part of spruce-fir management, they will be continued even when the budworm is not in outbreak. In contrast, if we make budworm management our major goal, the usual pattern of doing nothing unless an outbreak is in progress will likely repeat itself.

McFadden and Campbell (*in* Brookes et al. 1978) stated that "management practices in North American forests have rarely incorporated measures specifically designed to minimize future pest problems." In discussing the Douglas-fir tussock moth, these authors indicate clearly that much more information is needed on stand management possibilities. They do state that outbreaks "may tend to occur where stand biomass has exceeded long-term carrying capacity of the site."

The long-term study reported in Brookes et al. has contributed much toward

IPM of that insect. Evidently much more information is needed before a dependable hazard-rating system will be provided with an assurance that recommended applications to reduce hazard will work.

I could go on with other examples of methods which always seem to need further refinement before application will be recommended. I am sorry that I do not have the compendium on the gypsy moth *(Lymantria dispar)* from which to quote, but there have been papers developed from the Expanded Program which illustrate a similar need for further refinement. Brown et al. (1979) recommended reduction of the oak component as an obvious (their word) way to lessen defoliation and mortality in southern New England forests. They suggest increasing the component of white pine to enhance the value of the stands as well. This recommendation sounds familiar to all of us. Advice such as this may be refined as sites are studied more carefully and modern methods of systems analysis are applied. Such hazard studies may be very helpful to the manager interested in careful planning (Herrick et al. 1979).

WHAT REALLY CONTROLS OUR PEST MANAGEMENT DECISIONS?

The answers to this question have little to do with the insects themselves or the activities of forest entomologists. Yes, our work is necessary; we must provide information on the pests, methods for evaluating the damage they do, and procedures for reducing their overall impact. I well recall being told years ago that my job as a forest entomologist was to provide biological evaluations of forest insect problems. I was told that the economic and/or social aspects of the problem were for others to worry about. We are far better off today than we were at that time; now the silviculturists, economists, and entomologists are working together on these problems. Hopefully all three are developing more respect for and understanding of the work of their associates.

On the other hand, we seem to have less control over what we can do in pest management than we had 25 years ago. We are often frustrated by social (political) pressures that may prevent the use of superior alternatives. For example, we have a large and vocal pressure group that advocates the elimination of all chemicals on forest lands, private or public. The effectiveness of this group may be overcome through careful planning and public educational activities. However, if the cost of the educational process that will allow the land manager an opportunity to practice intensive forestry is excessive, then acceptance of the pest loss is the only valid alternative. Thus, social pressure has a decided impact on any decisions made and may even lead to reductions in forest productivity.

The major control on what we may accomplish in pest management is much easier to cope with. This is simply the market for the goods or services that we produce from and in the forest. One of the favorite comments of people in Maine is that if the paper companies had done something in the 1920's we would not have a budworm problem today. Such idle gossip shows a total lack of understanding of the ecosystem involved. Why? Because of lack of markets for the large surplus of available wood. At the time, the favorite species of the budworm (balsam-fir) was considered by buyers to be a weed species; spruce, on the other hand, was desirable.

How about ponderosa pine in Colorado and the Black Hills? Could we market enough of the small wood 50 years ago to use silviculture as a means of controlling mountain pine beetle *(Dendroctonus ponderosae)*? The answer is no, and in many areas we still have no available market for large quantities of small trees (fig. 3).

Figure 3.--Could thinning be applied profitably to stands such as this one infested by the mountain pine beetle?

Times have changed, however, and the demand for wood over wide areas of the nation has increased. We have a chance to do a reasonably good job of pest management if we can educate managers and landowners on the need for management and show them where they may market their products. The need for an effective educational program in extension to accomplish this goal is a high priority. The alternative to education is more restrictive

regulations on landowners through comprehensive forest practices legislation.

My comments on this question have related generally to wood products coming from the forest. The situation has improved regarding the sale of wood and wood products; thus we can discuss possibilities for intensive management with an optimistic view for the future.

Unfortunately we still must provide from the forest other values that most people seem to expect to be given to them at no cost. We expect to have available for everyone the esthetic values of the forest, the recreational opportunities for our citizens, vast areas of wilderness, a high production of game animals from privately owned lands, and clear water from forested watersheds. The investment in resource management to assure a continued availability of these values has been and continues to be a small fraction of the cost.

We can and we do provide these values in association with our wood production. Many owners of small woodlots are willing to pay taxes on their lands merely to hold them and are thus investing without a specific management objective; others desire to earn a profit on their holdings. Managers of larger tracts of forests require a return from their investment, but they are influenced by social pressures as well as their own interest in the future productivity of the land. Thus something gets done to assure a continued availability of values other than timber, but it is done with minimal investment that often comes from receipts of timber harvesting. If we really are convinced that the hazard from insect infestation is important to some of the values other than timber, we must develop accurate cost-benefit analyses that relate to those values.

ARE WE PREPARING FORESTERS TO MAKE DECISIONS ON COMPLEX RESOURCE MANAGEMENT PROBLEMS?

I'm sure you have all guessed by now that the questions I have posed and discussed have been leading to this issue. It is the key to our success in applying the concepts of IPM; and if hazard ratings are to have any validity in practice, the forester will have to find them reasonable and acceptable.

Keith Arnold (1976) made an observation that might cause some professors to go on the defensive, but the comment probably is more accurate than any of us want to admit: "Too many inadequately prepared professors in too many schools are training too many students to perform tasks that no longer exist." His article emphasized the need for people who are thoroughly prepared in both natural and social sciences and have received an educational program with emphasis on land capability as it relates to preservation, multiple use, and intensive production.

Jay Gruenfeld (1978) emphasized the need for industrial foresters who are technically competent but who also work well with people. He stressed the need for professionals who reason effectively, solve the right problems, communicate clearly, work well with people, have integrity, and produce. These characteristics make sense and are the traits that all professionals should develop.

Foil (1978) discussed the enrollment problem in some detail relative to undergraduate forestry programs. He correctly indicated that our discipline has lost ground in many universities. At one time, forestry was accepted in most institutions as a high-cost professional program. It is now one of the lower-cost programs on many campuses. The long-range implications of this sad situation are immediately apparent. The universities must continue to expand their offerings and meet the needs of the profession while adapting to stable or decreasing enrollments.

The articles I have quoted are just three of many, but they serve as examples of the thinking of people concerned about the education of our future land managers. We have been requiring more from our students as the years pass, but are we permitting them to acquire the skills they need? Are we requiring so much more in the technology area that we are not giving students time for expanding their ability to reason and solve problems? Sam Graham continually emphasized this point as he worked with students in forestry. He said, many times, that a forester must find time to sit on a log, look around, and think. I wonder if we are not substituting knowledge of mechanical monsters and ingenious data massaging devices, as well as memorization of facts and pressured short-term decisionmaking for that opportunity to sit on a log and think. A student cannot spend much time on reviewing literature when he or she must spend 4 or 5 hours a day correcting errors in computer programs or memorizing lists of scientific names. I'm not saying that the process of correcting a baffling error in a program or memorizing scientific names is unnecessary. I am saying that our balance sometimes seems to be faulty.

Every student forester should receive some background in hazard rating of forest stands and a course in forest entomology is mandatory--provided it is a course in FOREST entomology. We must realize that we are not preparing every forester as an

entomologist. Instead, we must provide foresters with enough of the basic information so that they can function effectively when pest problems are apparent in the stands they manage. We must present insects as a part of the ecosystem so the forester will know how his/her application of silviculture, management, or harvesting may affect the population of the pest. The concepts of hazard rating are very important in this instruction leading to an understanding of forest ecosystems and the role of pests in those systems.

Conclusions to this commentary on education relate directly to two fairly recent symposia. The first, known as the Roanoke Symposium (Glascock 1969), was on undergraduate education. The comments made there were similar to those quoted from more recent papers. Prof. Armstrong, in summarizing the material, quoted four major jobs of the college or university: (1) increase technical competence, (2) increase social competence, (3) integrate ideas and a comprehensive view, and (4) motivate and guide the student. The colleges were asked to recapture the sense of urgency and purpose which once dominated activity in education.

The second symposium, held at Oregon State University, was on Continuing Education (Krygier 1973). I quote from the conclusion of this publication because the statement is critical to all of us:

> The real test of the forestry graduate is not what he knows of forestry, but rather his ability to continue to learn and master the problems he encounters in managing forest resources.

Both symposia stress the need for broader and continued training of professional people. However, we can proceed only to a limited extent with our formal courses for students. We still must have top-quality people who are dedicated to professional ideals with a deep desire to provide the best management of resources possible within constraints of economic and social requirements.

CONCLUSIONS

This discussion has been purposely slanted to stress some of the negative aspects of our business. I have made comments about IPM indicating that I am not impressed with the results to date, but I hope I have indicated an expectation of improvement for the 1980's. Possibly I've overemphasized the effects of economic and social pressures on our abilities to accomplish newer and more effective techniques of management. I don't believe I've overstated the importance of education of both professionals and landowners to accomplish the level of integrated management required.

I am very pleased that this symposium on hazard-rating systems has been developed. Considerable progress has been made in development of hazard ratings, and it is appropriate to look closely at those accomplishments and at what we need to accomplish in the next decade. We have a fine opportunity now to apply hazard-rating systems. These opportunities did not exist when Miller, Keen, and Bongberg and associates were developing the rating systems for western pine beetle (*Dendroctonus brevicomis*). They sold people on the method at a time when success was much less likely and when wood requirements were much lower than at present. We should be able to do more under present conditions, and we can if we have practical people with the enthusiasm and persistence of those men of vision.

Demand for wood and wood fiber has never been greater, and we all know that future demand will be higher than at present. This situation can be viewed either as an opportunity or a disaster depending on your optimism or pessimism about application of good management practice. I prefer to view the future demand as an opportunity; with a real market for most of the wood produced, we can apply our knowledge of intensive management and succeed. Hazard rating becomes a part of this overall program. We must not be afraid to apply the knowledge we have available now, and we should be expanding our research on hazard ratings of forest stands.

I believe the variety of tools available for future management of pest problems will become even more restricted than at present. Our use of chemicals may be drastically reduced unless public attitudes change greatly. Our major weapon for the future may well be our preventive measures based upon hazard-rating systems. This, I see as the bright spot for all of us. The demand for wood fiber and wood products, which has climbed so drastically since the start of the energy crisis, gives us the opportunity to apply the principles of intensive management on a much wider scale. The 1980's may be the years we look back on as the time when the greatest improvements were made in increased productivity of our forests. I hope that all of us working in forest entomology will be proud of our share in that effort.

LITERATURE CITED

Arnold, R. K. 1976. Training needs for future managers of resource affairs. J. For. 74:519-522.

Baker, W. L. 1972. Eastern forest insects. 642 p. U.S. Dep. Agric. For. Serv., Misc. Publ. 1175.

Brookes, M. H., R. W. Stark, and R. W. Campbell, eds. 1978. The Douglas-fir tussock moth: a synthesis. 331 p. U.S. Dep. Agric. For. Serv., Tech. Bull. 1585.

Brown, J. H., Jr., D. B. Halliwell, and W. P. Gould. 1979. Gypsy moth defoliation: impact in Rhode Island forests. J. For. 77:30-32.

Chansler, J. F., and W. H. Klein. 1976. Proceedings of a symposium on the spruce budworm--Nov. 11-14, 1974, Alexandria, Virginia. 188 p. U.S. Dep. Agric., For. Serv., Misc. Publ. 1327.

Foil, R. R. 1978. The university environment and forestry education. J. For. 78:281-283.

Furniss, R. L., and V. M. Carolin. 1977. Western forest insects. 654 p. U.S. Dep. Agric. For. Serv., Misc. Publ. 273.

Glascock, H. R., Jr., ed. 1969. Proceedings: national symposium on undergraduate forestry education, Roanoke, Va. 108 p. Soc. Am. For., Washington, D.C.

Gruenfeld, J. 1978. Industry goals and forestry education. J. For. 76:360-361.

Herrick, O. D., D. A. Gansner, and P. S. DeBald. 1979. Predicting stand losses from the gypsy moth: an application of automatic interaction detection. J. For. 77:91-94.

Irland, L. C. 1977. Maine's spruce budworm program: moving toward integrated management. J. For. 75:774-777.

Jennings, D. T., F. B. Knight, S. C. Hacker, and M. E. McKnight. 1979. Spruce budworms bibliography. 687 p. Maine Life Science and Agriculture Exp. Stn. Misc. Rep. 213. University of Maine, Orono.

Kibbee, D. L., A. A. Berryman, G. D. Amman, and R. W. Stark. 1978. Theory and practice of mountain pine beetle management in lodgepole pine forests. 224 p. Forest, Wildlife, and Range Experiment Station, Univ. Idaho, Moscow.

Krygier, J. T., ed. 1973. Proceedings: continuing education for foresters. National symposium, Corvallis, Ore. Soc. Am. For., and Oregon State Univ., Corvallis, Ore.

Miller, J. M., and F. P. Keen. 1960. Biology and control of the western pine beetle. 381 p. U.S. Dep. Agric. For. Serv., Misc. Pub. 800.

Slocum, R. W., Jr. 1979. Affordable forestry. J. For. 77:487-488.

Stark, R. W. 1977. Integrated pest management in forest practice. J. For. 75:251-254.

Westveld, M. 1944. Forest management as a measure for controlling the spruce budworm. Paper presented to Maine Timberland Owners on Nov. 10, 1944, Bangor, Me.

Wickman, B. E. 1980. Increased growth of white fir after a Douglas-fir tussock moth outbreak. J. For. 78:31-33.

HAZARD-RATING SYSTEM DEVELOPMENT AND VALIDATION:

AN OVERVIEW

Roy L. Hedden[1]

Development of a forest pest management system is a three-step process consisting of (1) determination of pest impact; (2) identification of when and where damage will occur; and (3) determination if cost- effective, environmentally and socially acceptable methods of pest population management exist.

Quantification of impact requires a detailed understanding of the existing forest management regime. This knowledge is necessary in order to evaluate social, environmental, or economic effects of pest damage correctly. Lack of understanding can lead to either under- or overestimates of damage. For instance, evaluation of impact on pulpwood production in a stand managed for sawtimber will lead to a gross underestimate of impact since the value of sawtimber stumpage is many times higher than that of pulpwood.

Knowing when and where impact will occur is necessary when the pest management system emphasizes prevention. In this case, areas requiring treatment can be identified and treated to minimize damage and maximize control. Predicting where significant damage will occur will also lead to a more efficient system of remedial control. Population monitoring efforts can be concentrated in high-hazard areas during periods when the probability of significant damage is high.

Predicting when impact will occur generally falls in the broad area of pest population prediction. Identifying where damage will occur is normally considered the realm of hazard rating, although many hazard-rating systems are based upon a good understanding of pest population behavior.

If the forest insect pest causes significant damage, and if areas requiring treatments can be identified, then the third step in the process is to develop a cost-effective and environmentally and socially acceptable strategy for pest population management. This system can include both remedial and preventive methods. The pest management system developed must be compatible with the prevailing forest management regime and will ideally be a totally integrated subcomponent of this management program.

This paper deals with the second step of this three-step process--prediction of when and where impact will occur. Specifically, the development and validation of hazard-rating systems for forest pests is discussed.

APPROACHES TO HAZARD RATING

There are two general approaches to development of hazard-rating systems--biological and empirical. The biological or mechanistic approach is based upon a good understanding of the relationship between the insect, the host tree, and the environment. Generally this knowledge is accumulated over a long period of time and in discrete steps. It consists of identifying factors critical to the buildup of pest populations and components of host resistance, and determining the influence of the environment on these factors. Once these parameters have been identified, they may be used to develop a hazard-rating model. Because the model is based upon a detailed understanding of the target system, it can be easily evaluated for extrapolation to geographical areas different from where it was developed. Furthermore, because the model is based upon known biological linkages, it may easily be modified if necessary. Examples of such biologically based systems are the guidelines developed by the USDA Forest Service (Amman et al. 1977) and the Canadian Forestry Service (Safranyik et al. 1974) to reduce losses from the mountain pine beetle.

Frequently, the underlying relationships of the system are not well understood, or they are too complicated to allow a mechanistic model to be developed. For such cases an empirical model may be useful, especially if the model is applied only in the region where it was developed and under the conditions of development. A model of this type is based upon the apparent or correlative relationships among the insect, host, and the site. This type of model does not imply causation. Extrapolation of the model to other regions or for use under conditions other than those that prevailed at the time of development is difficult and must be done with caution. However, an empirical model can be used to suggest areas for further

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research and may ultimately lead to the development of a mechanistic model. Examples of empirical hazard-rating models are those developed by researchers at Stephen F. Austin State University (Hicks et al. 1980) and at the University of Arkansas (Ku et al. 1980) for predicting stand susceptibility to southern pine beetle attack.

Occasionally, researchers use biological relationships to develop an empirical model. A system using this strategy may be a compromise between biological realism and system complexity. An example of this type of model is Valentine and Houston's (1979) discriminant function for identifying mixed-oak stand susceptibility to gypsy moth defoliation.

Judgment is necessary to choose the best approach to pursue in developing a hazard-rating system. Factors to consider include the present state of knowledge about the pest complex, the time and money available for system development, and the ultimate use of the model. Generally, the mechanistic approach is justified (1) whenever a basic understanding of the system is essential to progress, or (2) when the state of knowledge is sufficiently advanced to make a useful biological model easily available. In contrast, an empirical model tends to be more economical and is especially useful when the objectives of the model are limited.

SYSTEM DEVELOPMENT

Several steps are common to development of all hazard-rating systems:

Identification of Users

Population definition
Data collection

Preliminary data analysis

Variable selection

Model development

Remember that the hazard-rating system is a small, although essential, part of the forest pest management program, which in turn is just a component of the prevailing forest management regime. Therefore, understanding the capabilities of the users, the type of information they have available, and the goals of the forest management program is essential. Unless the pest management system is compatible with the forest management regime, the hazard-rating system will most likely go unused. Ideally, users should be involved in the development of the hazard-rating system from the beginning. Acceptance of the system will be greater if users understand how it works and if they feel they have contributed to its development.

Identification of the target pest population is necessary in formulating the approach to model development. This step will determine the nature and extent of the data collected. For instance, developing a hazard-rating system for the Douglas-fir beetle in the forests of central Idaho is not the same as developing a system for the coastal forests of Washington and Oregon. The climate in the two areas is obviously different, the ecological position of the host tree is not the same in each region, and the behavior of the beetle is also likely to be different in the two areas.

Whether or not new data for model development must be collected depends upon the state of knowledge about the pest system and the amount of appropriate data previously collected. In some cases a model may be developed on the basis of past work. An example of such a system is the one developed by Schmid and Frye (1976) for rating Engelmann spruce stands for susceptibility to spruce beetle outbreaks. However, in many cases new data are required. Occasionally, experimentation and data collection are limited to filling gaps in existing knowledge.

When little is known about the relationships among the insect, the host tree, and the environment, extensive data collection and/or experimentation will be necessary. Generally, data are collected on several variables simultaneously. The variables may not have known relationships to pest biology; however, they should be useful for defining potential relationships among insect, host, and environment.

Within the framework of the target population, data should be collected from as diverse a range of conditions as possible. Sample plots should be allocated in a manner so that the data collected are compatible with proposed data analysis procedures. A good experimental design is necessary so that maximum information can be extracted from the data. A good design also assists in interpolation of the results within the range of the data.

When large amounts of data are collected, preliminary analysis is important. The data may require extensive verification and editing. In addition, poststratification of the data set may be necessary for effective analysis. For instance, when Ku and his coworkers (1980) were developing models to predict stand susceptibility to southern pine beetle infestation, they found that dividing the data into two sets based upon the presence or absence of stand disturbance was necessary for analy-

sis and interpretation of the data. Otherwise the apparent relationships between beetle incidence and the site-stand variables were masked.

When data have been collected on many variables, the next step is to identify those that contribute information to the hypothesis under consideration. These variables, or subsets of them, can then be used in model development. Many statistical tests ranging from simple univariate *t*-tests to the more sophisticated multivariate techniques such as discriminant and factor analysis can be used for variable reduction. Ultimately, the variables selected for inclusion in a model must be based not only upon the results of statistical tests, but upon their ease of interpretation and their usefulness in existing forest and pest management systems. It is unlikely that a model based upon variables for which data are difficult and expensive to obtain will be implemented and used. Whenever possible, variables that use existing information should be selected.

After candidate variables have been identified, a model can be developed. It may be either qualitative or quantitative, empirical or mechanistic. The exact form of the model will depend upon the knowledge about the pest complex and upon the proposed use of the model. A very simple qualitative model might suffice when assignment of broad categories of risk or hazard is necessary. An example of such a risk model is the one developed by Salman and Bongberg (1942) for classifying merchantable ponderosa pine trees for selective cutting to reduce losses from bark beetles. This system used four broad categories of risk based upon crown characteristics. Validation of this system showed it to be adequate for the purpose for which it was developed--partial cutting.

Quantitative models can take many forms. They might be expressed as systems of discriminant functions, regression equations, or probability functions. Quantitative models can be used to generate broad classes of risk or hazard that can be used in turn to set treatment guidelines. The stand hazard-rating system for rating stand susceptibility to southern pine beetle infestation developed by Ku and his coworkers (1980) has been used in this manner. Based upon a score derived from a discriminant function, a stand is classified as to high, medium, or low susceptibility to infestation.

Ultimately, the exact form of any model will depend upon the complexity and understanding of the target system, the intended use of the model, and the nature of the existing forest management regime.

SYSTEM VALIDATION

After a model has been developed, it must be validated. Validation can occur either before or after implementation. In general, some form of validation should be done before the system is put into use.

There exists a hierarchy of validation: (1) testing the model against the data from which it was developed, (2) testing it on a subset of the original data that were set aside for this purpose before the model was developed, and (3) testing the model on a completely independent set of new data.

Obviously, good performance against the data from which a model is developed is to be expected and does not represent a very rigorous test of the model. Testing the model against a subset of the original data set aside for this purpose is more powerful, but this validation procedure is constrained by the conditions prevailing when the original data set was collected. This procedure does not allow the model to be tested for robustness to changing spatial and temporal conditions.

The most rigorous test is validation against a wholly independent set of data. Such a test will indicate how robust a model is to changing conditions. Furthermore, if the range of conditions is greatly different from those that prevailed when the model was developed, then the validation procedure will indicate whether the model can be extrapolated to cover conditions outside the range of the original data.

This validation phase is potentially the most important in developing hazard-rating systems. Unfortunately it is the step most often ignored. Many researchers feel that their obligations end when a model is developed. In reality, system development is not complete until the model has been tested and validated. Model validation should be a continuing process where feedback from it is used to modify and update the system. Schematically, this process is as follows:

Identification of users

Development

Modification and Refinement

Validation

Implementation

Use

IMPLICATIONS FOR FOREST MANAGEMENT

A forest pest management system is a subcomponent of a forest management regime.

One important attribute of a pest management system is the ability to predict when and where a pest outbreak will occur. Hazard-rating models assist in this process. If a model is to be used, it must be compatible with the existing management regime. Furthermore, management decisions will only be as good as the information on which they are based. Therefore, basing the model on the highest quality information available and stating the limitations of the model is critically important. Model development and validation must be a continuing process, and new knowledge must be incorporated when appropriate. Ultimately, the success of the entire hazard-rating effort depends upon whether this technology meets the users' needs.

LITERATURE CITED

Amman, G. D., M. D. McGregor, D. B. Cahill, and W. H. Klein. 1977. Guidelines for reducing losses of lodgepole pine to the mountain pine beetle in unmanaged stands in the Rocky Mountains. 19 p. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. INT-36. Intermountain For. Range. Exp. Stn., Ogden, Utah.

Hicks, R. R., Jr., J. E. Howard, K. G. Watterston, and J. E. Coster. 1980. Rating forest stand susceptibility to southern pine beetle in east Texas. For. Ecol. Manage. 2:269-283.

Ku, T. T., J. M. Sweeney, and V. B. Shelburne. 1980. Site and stand conditions associated with southern pine beetle outbreaks in Arkansas--a hazard-rating system. South. J. Appl. For. 4:103-106.

Safranyik, L., D. M. Shrimpton, and H.S. Whitney. 1974. Management of lodgepole pine to reduce losses from the mountain pine beetle. Environment Canada, Forestry Service. For. Tech. Rep. 1, 24 p.

Salman, K. A., and J. W. Bongberg. 1942. Logging high risk trees to control insects in pine stands of northeastern California. J. For. 40:533-539.

Schmid, J. M., and R. H. Frye. 1976. Stand rating for spruce beetles. 4 p. U.S. Dep. Agric. For. Serv., Res. Note RM-309. Rocky Mountain For. Exp. Stn., Missoula, Mont.

Valentine, H. T., and D. R. Houston. 1979. A discriminant function for identifying mixed-oak stand susceptibility to gypsy moth defoliation. For. Sci. 25:468-474.

G. D. Hertel[1]

To help meet national needs for timber, we can increase timber supplies by intensifying management, improving utilization, and reducing losses from fire, insects, and diseases. One potential area for reducing losses centers around the ability to "pest proof" stands. New developments in resource protection must be effective, practical, economical, and environmentally sound. They should also be an integral part of total resource management planning and actions. This prevention concept has been highlighted in the Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA); its amendment, the National Forest Management Act of 1976 (NFMA); and the Cooperative Forestry Assistance Act of 1978.

Historically, most efforts have been aimed at the short-term direct control of forest pests. However, in the past 10 years, interest and support for developing approaches to prevent and/or reduce the severity of pest outbreaks has increased in several regions of the country. Recently, research and development efforts have produced a great deal of new and improved technology, which has created, by its volume alone, the problem that now faces us. How can we get this information communicated efficiently to forest managers/landowners? In reviewing this problem, I will discuss the technology transfer process, present a summary of hazard-rating systems now being implemented in the United States, and specifically examine implementation experiences with southern pine beetle (SPB) hazard ratings. Hopefully, my comments, along with those presented in other symposium papers will provide you with a basic format for implementing new technology.

TECHNOLOGY TRANSFER (RESEARCH UTILIZATION)

The Process

Today there is a great deal of interest in asking questions of the research community, getting answers, and making sure those answers are utilized. In very simple terms, this forms the basis for a technology transfer model (fig. 1).

Basically, technology transfer is a process by which research results are com-

Figure 1.--A simple technology transfer model (from Essoglous 1975).

municated to practitioners for their use. These results will be more easily transferred if there was joint identification of a need when the research was initially planned. There are certain elements (fig. 2) that must be considered in the transfer mechanism noted in figure 1 (Creighton and Jolly 1979).

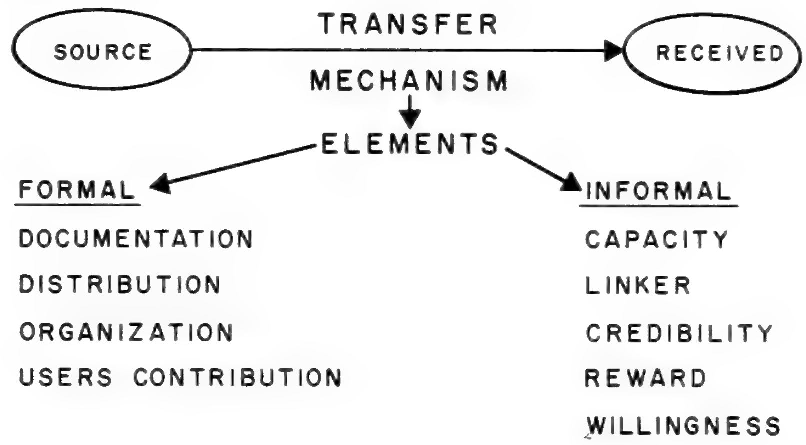

Figure 2.--Elements of the transfer mechanism.

Formal Factors

Documentation.--Technology cannot be transferred if it cannot be communicated in an understandable form. Specialists and professional practitioners in resource management are a critical audience. Their time is valuable, and competition for it is intense. They respond to brief, convincing, and attractively packaged information. The "How-To" handbooks developed by the three Combined Forest Pest Programs and fact sheets developed by the Southeastern Area, State and Private Forestry (S&PF), are good examples of this type of documentation.

Distribution.--This factor is the physical channel through which technology flows, involving the number of information entries, ease of access to the available information, the formal means by which this information is distributed, and the ways it impacts the user. Apparently, improvements in information delivery systems have aided in accelerating the technology transfer process.

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Organization.--Some potential users of technology and linkers are part of a formal organization. The organization always exerts an impact on the transfer effort. Some organizations, because of their sheer size and complexity, may intentionally or unintentionally obstruct change and innovation. Some are burdened with too many "recipe" directives on how to manage resources or situations. Change is a way of life. Resistance to change is also a way of life. For change to occur, we must overcome resistance to change and provide the proper organizational environment to encourage constructive improvements in operating procedures.

User's contribution.--Technology transfer is enhanced when potential users of the technology help decide what projects are undertaken. Collaboration between researchers and users at the "ground floor" level ensures that research meets practical needs, and early involvement of user makes it more likely that users will support implementation of research that may seem radical or avant garde. Research has a better chance of being accepted and used if researchers, specialists, practitioners, and administrators have participated at every stage of the planning, execution, and interpretation of the research.

Informal Factors

Informal factors involved in the success of technology transfer include individual traits, capabilities, perceptions and predispositions that can affect the success of a technology transfer effort. Thus selection of "linkers" with the proper characteristics is extremely important.

Capacity.--This factor refers to the ability of the potential user to understand and utilize new and innovative research results. Innovative individuals serve as demonstrators of new practices and make an important contribution to the transfer of new technology. These people will be the first to try new ideas, methods, or practices. By determining their attitudes, one can predict whether there is potential for picking up and encouraging the use of a new technology in a particular setting.

Linkers.--Linkers are individuals who provide technical advice or who link or seek out and help incorporate new technology into the operational program of their own or another organization. They might be thought of as the gatekeepers, opinion leaders, or early adopters of new or improved ideas.

Credibility.--Credibility is the users' assessment of the reliability of the information that is presented to them and the "trustworthiness" of the individual(s) who produced or transferred the technology.

Reward.--This factor is concerned with an individual's self-satisfaction and perceived recognition by his or her organization or peer group. It has been said that rewards are the glue which holds organizations together and provides the response to individual needs for recognition of accomplishment. A predefined and operating system of scientific and organizational rewards for research/implementation/use will definitely enhance researcher/linker/ user involvement.

Willingness.--Willingness relates to an individual's or organization's ability or desire to accept change. Resistance to technological change is a major barrier in transfer efforts. Unwillingness to face the price of innovation is a major problem holding back technological progress.

Approaches in a Current Program

Browning and Colling (1979) discuss the approach taken by the Forest Service's Surface Environment and Mining (SEAM) Program. They point out that the technology transfer process requires well-defined and functional arrangements for getting the job done (fig. 3). Each step in the SEAM process is important and requires a group (researcher-linker-user) effort.

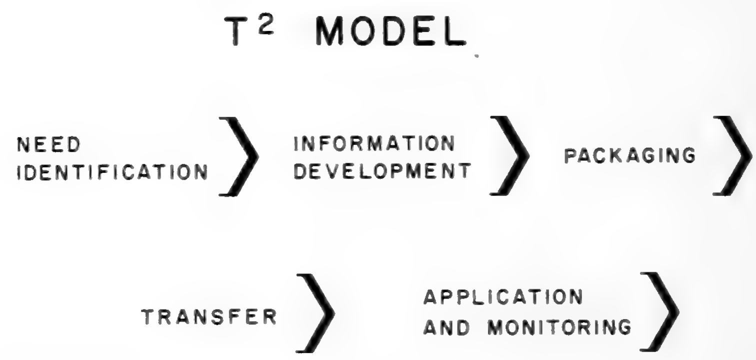

Figure 3.--SEAM T^2 model.

The components of this approach may be abstracted as follows:

(1) Identification of need.--A great deal of effort must be made by all parties to understand just what they need and whether information is already available that can solve the problem. Input into the research planning process enhances recognition of work and the setting of feasible goals. By being involved, the user will more readily understand and apply the end product. This early involvement establishes

awareness, commitment, and ownership. During the research planning phase, the investigator should develop a tentative applications plan. Such a plan would provide more options for information development, packaging, transferring, and applying the information than might be possible if applications were considered later. Recently, the Forest Service has developed a guide to aid in transferring available research results (Marx n.d.). Consideration should be given to steps in the guide at an earlier phase in the research process.

(2) Information development.--After the research has been planned and budgeted, the development phase begins. Review teams are established to act as advisors to the Program and, indirectly, to the scientists. Membership of these teams will represent technical, administrative, and user-oriented interests. These review groups serve several functions:

1. They provide recommendations on program direction and priorities, prepare and review plans, and evaluate accomplishment.

2. They build awareness and support for research and applications efforts in the user community.

3. They evaluate research results and facilitate exchange of information in the research and user communities.

4. They determine what technology is ready for implementation and when, how, to whom and in what form it should be implemented.

(3) Packaging.--Effective packaging involves a wide range of skills and techniques, including writing, editing, design, advertising, audiovisual expertise, training, and consultation. To achieve effective packaging, specialists must prepare the information in a manner that will best meet the needs of a particular audience.

The packaging effort can be completed through contracting or by using writer/editors, technical specialists, and staff.

(4) Transfer.--Technology transfer ranges from making people aware of available information (using mass media) to instructing them on how they can implement technology (*see* Muth and Hendee 1980). My definition of implementation for this paper includes one-on-one interaction with users, as described in phases 1-5 in table 1. Interaction is the key for successful testing and validation, implementation, and finally for actual use (phases 6 and 7, table 1). Scientists, linkers (if needed), and users must work together if transfer is to take place.

Table 1.--Description of the implementation phase (Agarwala-Rogers and Rogers 1978)

1. Planning for adoption
2. Learning to use the innovation
3. Adapting the innovation to local conditions
4. Beginning actual use, or installation, of the innovation
5. Evaluation of (1) the degree to which an innovation meets the felt need, and (2) its other consequences
6. Decision to continue using, or to discontinue, the innovation
7. Institutionalization of the innovation into the ongoing activities of the adopter

(5) Application and monitoring.--Monitoring the acceptance, use, and modification of information as it is passed through linkers (State and Private Forestry, Extension Service, State forestry commissions, etc.) to users is important. There is need for specific, measurable objectives that serve as the basis for evaluating the transfer effectiveness. Users often modify the information, making it more useful. But if there are no close ties between the user and the researcher or linker, no one else would ever benefit from the modification. Specialists from State and Private Forestry, Cooperative Extension Service, and State forestry agencies have the responsibility not only to facilitate the implementation of technology, but also to evaluate the effectiveness of new or improved technology once it is accepted and put into use. They must make sure those successful experiences are documented.

The preceding was a general discussion of the technology transfer process. The rest of this paper will discuss how some of these procedures were followed in order to implement stand hazard-rating system.

HAZARD-RATING SYSTEMS BEING IMPLEMENTED

A number of hazard rating systems are being implemented throughout the country (table 2). Others are still in the process of being developed or validated. A few are operational.

A great deal of effort has gone into getting these systems to the stage they are in today. They have gotten to this point through various combinations of need, people, and money. All too often, the

Table 2.--Hazard rating system being implemented[1]

Region/Area	Insect	Host
1	Mountain pine beetle	Lodgepole pine
	Mountain pine beetle	2nd growth ponderosa pine
	Spruce beetle	Engelmann spruce
	Fir engraver	Grand fir
2	Spruce beetle	White spruce
4	Mountain pine beetle	Lodgepole pine and 2nd growth pine
	Spruce beetle	Engelmann spruce
	Western pine beetle	Ponderosa pine
	Western spruce budworm	Douglas-fir, grand and subalpine fir
5	Douglas-fir tussock moth	Douglas-fir
6	Mountain pine beetle	2nd growth ponderosa pine
NA	Pine root collar weevil	Scotch pine
	Saratoga spittle bug	Red pine
	Spruce budworm	Balsam-fir
SA	Reproduction weevils	Loblolly, slash, and shortleaf pines
	Southern pine beetle	Loblolly and shortleaf pines

[1] This information was obtained from the Forest Pest Management (State and Private Forestry) Offices in each respective Region/Area.

necessary staffing and money cannot be found when they are most important: when the technology can be moved from the research and validation phase to the operational-use phase.

Experiences in ESPBRAP

To give you some insight about what goes on during the implementation of new technology, I would like to review my experiences with hazard/risk-rating systems supported by the Expanded Southern Pine Beetle Research and Applications Program (ESPBRAP).

The hazard/risk-rating implementation experiences have been ESPBRAP's most successful. But I can look back on the development of stand hazard-rating models and suggest doing things differently (good old hindsight!).

We could have improved the development phase by having potential users more involved in the research planning and coordination. Also, we could have established a closer link, at least during the last few years, between investigators working in the coordinated regional site/stand project and in the population dynamics subject areas.

The primary task of the coordinated regional site/stand project was to determine what variables were consistently related to outbreaks across a large segment of the beetles' range (Coster and Searcy 1980). The investigators used these data to develop hazard-rating systems and have presented their findings in scientific articles (Belanger et al. 1980; Hicks et al. 1979; Ku, Sweeney, and Shelburne 1980; Kushmaul et al. 1980; Lorio 1978; Lorio and Sommers 1980; and Mason 1980).

As part of the effort to make this information available to the forestry community, Thatcher (1978) suggested that ESPBRAP establish technology transfer teams to communicate results to practitioners. Two of the teams recommended were the stand susceptibility rating for SPB attack team and the silvicultural practices for preventing or reducing SPB damage. The SPB Technology Transfer Task Force (Southeastern Area, State & Private Forestry 1979) combined the two teams into one and recommended that further work in this area be given high priority. Roger Belanger, team leader for the Silvicultural Practices and Stand Hazard-Rating Systems Technology Transfer Team, conducted awareness workshops. Belanger and his team developed an SPB Fact Sheet (Southeastern Area, State & Private Forestry 1980), and wrote sections or chapters for the Southern Pine Beetle Research, Applications, and Implementation Activities for the southern forestry community report (Belanger et al. 1979), the site/ stand characteristics technical bulletin, and the ESPBRAP compendium. Other scientists, in-

cluding Timothy Ku, Garland Mason (supported by SA-S&PF), and Ray Hicks, have been very active in their respective States. Currently, SPB hazard-rating systems are being implemented in Arkansas, Georgia, Louisiana (National Forests), and Texas (table 3). More are being considered for Alabama, Louisiana (private ownerships), and South Carolina. As a sample of our experiences, I would like to discuss some of the implementation experiences in Georgia, Arkansas, and Louisiana.

Georgia (Belanger)

Working in the Georgia Piedmont, Roger Belanger's team (1980) developed a discriminant model using six variables--radial growth last 5 years (mm) of dominant and codominant pines, percent live crown (average of all pines), percent clay in surface (0-15 cm) horizon, depth of *A* horizon (cm), percent loblolly pine in total pine component and percent clay per cm in *A* horizon)-for undisturbed natural stands.

Another model (land manager's) was constructed with easy-to-measure variables-percent live crown (average of all pines), radial growth for last 5 years of dominant and codominant pines, percent loblolly in total pine compenent, and depth (cm) of *A* horizon. The land manager's model is currently on Forest Pest Management's (FPM) computer in Atlanta and can be accessed by anyone with an interactive computer terminal.

Roger and Terry Price, forest entomologist with the Georgia Forestry Commission, developed a good working relationship. Terry is serving along with Roger on the Silvicultural Practices and Stand Hazard Rating Technology Transfer Team. Together they developed a simple qualitative system that uses stand, tree, and site characteristics to rank stand susceptibility to SPB attack. Their system is compatible with the procedure service foresters use to develop forest management plans (table 4). Georgia Forestry Commission service foresters are using this system in the upper Piedmont.

Arkansas (Ku)

Timothy Ku's group in Arkansas worked in shortleaf and loblolly pine types and developed a hazard-rating system for natural stands on upland flat sites (table 5). The key variables in their model are total basal area, hardwood basal area, stand age, and radial growth during the last 10 years.

A very positive note in the development of this system was that the Arkansas Forestry Commission assisted with field collection of the data. Consequently, the Forestry Commission was more receptive to using the final product.

Table 3.--Implementation of hazard ratings for SPB in the South

	System used	Landowner	Modified	Interaction
Arkansas	Ku	Private	No	U. Ark. (Ku) & State - Ark. Forestry Comm. (Northum)
Alabama	Mason Belanger	Private Private	No No	Ala. Forestry Comm. (Hyland) and S&PF (Oliveria)
Louisiana	Lorio	National Forest	Yes	Natl. Forest (Cox, Barrett); Southern Stn. (Lorio); S&PF (Nettleton)
Georgia	Belanger	Private	Yes	SE Stn. (Belanger); Ga. Forestry Comm. (Price)
Texas	Mason/Hicks	Private and industrial	Yes	Stephen F. Austin (Mason); Tex. For. Serv. (Billings)
Louisiana	Mason	Private	No	La. Forestry Comm. (Jeane); S&PF (Oliveria)

Table 4.--Ranking the susceptibility of stands to SPB attack

Stand		
1. Shortleaf pine $\geqq$ 50% total pine	Yes___	No___
2. Hardwood component $\leqq$ 25% total stand	Yes___	No___
3. Pine BA $\geqq$ 130 ft^2/acre	Yes___	No___
Representative Tree		
4. Radial growth (last 5 years $\leqq$ ½ inch	Yes___	No___
5. Live crown ratio $\geqq$ 40%	Yes___	No___
Surface Soils 0-6 inches		
6. Micaceous red clays	Yes___	No___

The yes answers are totaled and a hazard ranking and need for cultural treatment given according to the following diagram:

	Hazard Ranking						
	Low		Moderate			High	
Total of "yes" answers	0	1	2	3	4	5	6
Cultural treatment	Not needed					Needed	

The University of Arkansas at Monticello recently cooperated with the Arkansas Forestry Commission and the Southeastern Area State and Private Forestry to print a leaflet describing the use of Ku's hazard-rating system. In May, this pamphlet was used in a hazard-rating training session for selected Arkansas Forestry Commission service foresters. A Statewide workshop for the user groups has been planned through the Cooperative Extension Service to be conducted by the University, State, and FPM personnel to implement the system fully.

Louisiana (Lorio)

A number of years ago, Pete Lorio began collecting site/stand/tree data in infestations located on the Kisatchie National Forest (KNF). Results from that study and work funded by ESPBRAP led to his use of available resource data to develop a stand risk-rating method (Lorio 1978). Five variables (forest type, stand condition class, method of cut, operability, and site index (*see* Lorio and Sommers 1980 for definitions of variables) found on the Forest Service's computerized Continuous Inventory of Stand Conditions (CISC) are used in rating individual stands. Ratings based on this approach

Table 5.--SPB stand hazard rating system for Arkansas

Stand score = -1.50(TBA) + 3.3(age) + 64.3 (growth) + .93(HBA)

TAB = total basal area (ft^2/ac)

Age = stand age (years)

Growth = average radial growth in 10 yr (nearest 0.1 inch)

HBA = hardwood basal area

Stand Susceptibility

Score	Susceptibility
101 and above	Low
1 to 100	Medium
Less than 1	High

are currently being used by the timber staff and ranger districts to select stands for regeneration and intermediate cuts during the period FY 1984-93.

The KNF provided study sites and worked with Pete Lorio on clarification and interpretation of the CISC information. Work continues in this vein as Kisatchie's timber staff and Lorio have prepared a set of stand risk criteria for use by prescriptionists on an optional basis.

Beginning this fall, foresters writing new prescriptions will use the KNF supplement (table 6) and hazard rate 10 percent of the stands. Up-to-date SPB hazard ratings incorporated into the CISC data base will then be available to resource managers to aid them in their decisionmaking process. Monitoring of this effort over time will be done by Forest Pest Management. A Research-FPM team is currently drawing up guidelines for this evaluation.

FPM will also provide any requested training and, through the use of their Southern Pine Beetle Informational System (SPBIS), will collect the necessary data to evaluate the hazard-rating system. SPBIS was developed by Jim Smith (Pineville) and Bob Uhler (Atlanta) to keep records on SPB control when National Forest districts had suppression projects.

HOW DO HAZARD-RATING SYSTEMS FIT INTO IPM?

The successful management of commercial forests requires a thorough knowledge of the biological and ecological factors regulating them. Insects are an important component of this ecosystem, so they must be considered in managing forests. Integrated pest management (IPM) is a system to manage the insects in a total resource management context (Coster 1980).

From this IPM approach, resource managers should obtain information (on population dynamics of the insects and forest stands, treatment strategies, and impacts on resources) and procedures to help them make proper decisions on managing the forest. This information can be obtained from pest management specialists working for State forestry commissions, industry, Cooperative Extension Service, and the USDA Forest Service. This information is brought together in a benefit/cost integration framework to help managers make the best decisions.

The decision support system is an information-gathering and -collating system. The resource manager/landowner will bear the final responsibility for any decisions made. In deciding what to do about a specific insect, the manager must receive support information in proper sequence: detection, evaluation, potential

Table 6.--Criteria used by Kisatchie National Forest for high and medium risk classifications of stands for SPB

A. Stands with forest types loblolly pine, shortleaf pine, loblolly pine-hardwood, or shortleaf pine-oak will have a high or medium stand risk classification according to total stand height and pine basal area as follows:

Total height	High risk	Medium risk
	----------Basal area-----------	
56-65		>80
66-75	>90	80-90
76-105	>90	70-90
106+	>100	90-100

B. Stands with forest types slash pine, longleaf pine, or bottomland hardwood-yellow pine will have a medium risk classification according to total stand height and pine basal area as follows:

Total height	Basal area
66-75	>80
76-105	>90
106+	>100

[1] Taken from Forest Service Handbook, Pineville, La., Sept. 1979, FSH 2409.21d, R-Compartment Prescription Handbook, Kisatchie National Forest Supplement No. 5. p. 600-1 to 600-3.

effects on management goals, identification of management options, identification of environmental and social consequences for each alternative, identification of benefit/cost relationships for each alternative, comparison of alternatives, integration of resource and pest management programs, and implementation.

Decisions are made prior to the evaluation (Decision 1: Are insects important to management?), after effects on management goals are evaluated (Decision 2: Will goals be affected?), and after comparison of the benefits and cost of management alternatives (Decision 3: Which management options are appropriate?).

Hazard ratings are just one part of the total package needed for a decision support system, however. Technology that rates the susceptibility of stands to SPB attack can be used as an aid in detection, evaluation, setting control priorities, and prevention.

CONCLUSION

We all realize that much more technology will be used if it relates to an insect with known negative impacts. Once we have determined how serious an insect problem is, the answers to when it occurs, where it occurs, and how to solve the problem will be eagerly sought out.

A tremendous amount of cooperation is required if we want to move from identifying the need through the subsequent research, and on to implementation and use. Cooperative relations between USDA Forest Service (Research, State and Private Forestry, National Forests), State forestry agencies, Cooperative Extension Service, consultants, industrial foresters, and the forestry community in general must be strengthened so that the needs of land owner/managers are satisfied.

In short, no matter how sophisticated our technology, the main difficulties in implementing transferable technology from the researcher to the user are still "people" problems. To quote a recent article in *Newsweek*, "Solutions, we must remember, are very much like problems: they are rooted in people, not in technology. Schemes that try to devise miracles to bypass people, negate, deny, nullify, or minimize people, will not work, or at least they will not work on a planet on which it is people who are expected to live" (Sale 1980).

ACKNOWLEDGMENTS

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LITERATURE CITED

Agarwala-Rogers, R., and E. M. Rogers. 1978. Manual for technology transfer specialists. Instit. for Communication Res. Stanford Univ., Palo Alto, Calif. U.S. Dep. Agric. For. Serv., Surface Environment and Mining Prog., Washington, D.C.

Belanger, R. P., R. N. Coulson, J. Lewis, T. L. Payne, F. M. Stephen, J. W. Taylor, J.G.D. Ward, and R. F. Westbrook. 1979. Southern pine beetle research, applications, and implementation activities for the southern forestry community. U.S. Dep. Agric. For. Serv., Comb. For. Pest Res. Develop. Prog., Pineville, La. (Unpublished but available from IPM Program, 2500 Shreveport Highway, Pineville, LA 71360.)

Belanger, R. P., R. L. Porterfield, and C. E. Rowell. 1981. The development and validation of systems for rating the susceptibility of natural stands in the upper Piedmont of Georgia to attack by the southern pine beetle. *In* Hazard-rating systems in forest insect pest management: symposium proceedings. [Athens, Ga., July 1981.] R. L. Hedden, S. J. Barras, and J. E. Coster, coords. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-27.

Browning, E. R., and G. Colling. 1979. The SEAM technology transfer process. *In* Highlights technology transfer workshop. [Tucson, Ariz., Feb. 1979.] p. 8-11. U.S. Dep. Agric. For. Serv. U.S. Govt. Print. Office 0-280-931/ FS-105.

Coster, J. E., and J. L. Searcy, eds. 1980. Site, stand, and host characteristics of southern pine beetle infestations. U.S. Dep. Agric., Tech. Bull. 1612. Comb. For. Pest Res. Develop. Prog., Pineville, La.

Coster, J. E. 1980. Developing integrated management strategies. *In* The southern pine beetle. R. C. Thatcher, J. L. Searcy, J. E. Coster, and G. D. Hertel, eds. U.S. Dep. Agric. For. Serv., Tech. Bull. 1631. Comb. For. Pest Res. Develop. Prog., Pineville, La.

Creighton, J. W., and J. A. Jolly. 1979. Technology transfer and utilization. *In* Highlights technology transfer workshop. [Tucson, Ariz., Feb. 1979.]

p. 8-11. U.S. Dep. Agric. For. Serv. U.S. Govt. Print. Office 0-280-931/ FS-105.

Essoglou, M. E. 1975. The linker's role in the technology transfer process. *In* Technology transfer in research and development. J. A. Jolly and J. W. Creighton, eds. 90 p. Naval Postgraduate School, Monterrey, Calif. NPS-55JO75120.

Hicks, R. R., Jr., J. E. Howard, K. G. Watterston, and J. E. Coster. 1980. Rating forest stand susceptibility to southern pine beetle in east Texas using probability functions. For. Ecol. Manage. 2:269-283.

Ku, T. T., J. M. Sweeney, and V. B. Shelburne. 1980. Site and stand conditions associated with southern pine beetle outbreaks in Arkansas--a hazard-rating system. South. J. Appl. For. 4:103-106.

Kushmaul, R. J., M. D. Cain, C. E. Rowell, and R. L. Porterfield. 1979. Site and stand conditions related to southern pine beetle susceptibility. For. Sci. 25:656-664.

Lorio, P. L., Jr., 1978. Developing stand risk classes for the southern pine beetle. 9 p. U.S. Dep. Agric. For. Serv., Res. Pap. SO-144. South. For. Exp. Stn., New Orleans.

Lorio, P. L., Jr., and R. A. Sommers. 1981. Stand risk classification for the southern pine beetle with available resource data. *In* Hazard-rating systems in forest insect pest management: symposium proceedings. [Athens, Ga., July 1980.] R. L. Hedden, S. J. Barras, and J. E. Coster, coords. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-27.

Marx, H. G. [n.d.]. Guide to help develop a technology transfer plan. 26 p. U.S. Dep. Agric. For. Serv., Washington, D.C.

Mason, G. N., R. R. Hicks, Jr., C. M. Bryant V., M. L. Mathews, D. L. Kulhavy, and J. E. Howard. 1981. Rating Southern Pine Beetle Hazard by Aerial Photography. *In* Hazard-rating systems in forest insect pest management: symposium proceedings. [Athens, Ga., July 1980.] R. L. Hedden, S. J. Barras, and J. E. Coster, coords. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-27.

Muth, R. M., and J. C. Hendee. 1980. Technology transfer and human behavior. J. For. 78:141-144.

Southeastern Area, State and Private Forestry, USDA Forest Service. 1979. Southern pine beetle technology transfer task force report. 23 p. U.S. Dep. Agric. For. Serv., Tech. Publ. SA-TP7. Atlanta, Ga.

Southeastern Area, State and Private Forestry, USDA Forest Service. 1980. Systems to rate the susceptibility of pine stands to southern pine beetle attack. Technol. Update. SPB Fact Sheet No. 9. Southeast. Area, State and Priv. For., Atlanta, Ga.

Thatcher, R. C. 1978. Communicating research results to practitioners--a technology transfer plan. 12 p. U.S. Dep. Agric. For. Serv., Comb. For. Pest Res. Develop. Prog., Pineville, La. (Unpublished, but available from IPM Program, 2500 Shreveport Highway, Pineville, LA 71360.)

USER EXPERIENCES: AN OVERVIEW

Caleb L. Morris[1]

As the lady of the night responded when propositioned at two in the afternoon, "Isn't it a bit early?"

Such may be the case in our attempt to evaluate the response of users to the variety of hazard- or risk-rating systems for forest pests currently available across the United States. Why? Because most are of fairly recent origin. Nonetheless, there have been several systems available to forest managers for a number of years. One is the classic "tree classification system" developed by Keen (1936) for western pine beetle in old-growth ponderosa and Jeffrey pine, a system based on age and crown vigor. Later, Salman and Bongberg (1942) developed a variation to meet somewhat different management objectives in California, essentially utilizing crown characteristics alone. Still later, additional modifications were developed by Miller and Keen (1960) utilizing various indicators of poor health.

The California risk-rating system continues to be used in that State and in the Pacific Northwest where appropriate silvicultural conditions and resource management objectives exist, primarily sanitation/salvage cuts (Larry Freeman and Paul Buffam, personal communications). The California system has been widely applied via sanitation/salvage logging on private and public forests of the interior (ponderosa) pine type in northeast California and southern Oregon. The extent of its use is difficult to determine, but there may be 2 to 3 million acres of applicable forest that have been processed to some degree by sanitation/salvage logging. It has been adopted as a standard management practice by the USDA Forest Service in Region 5 and many timberland owners in California and Oregon (Smith et al. 1981).

Other coniferous bark beetle risk-rating systems have followed. One, a risk-rating system for mountain pine beetle in unmanaged stands in the Rocky Mountains (Amman et al., 1977) is reported by the senior author as having met with favorable reception, largely through the efforts of FPM entomologists. This system is widely used in Montana, with some application in Idaho, Utah, and Colorado. In Oregon and Washington, a slightly modified risk-rating system based on age and d.b.h. is utilized (Paul Buffam, personal communication). Most of the lodgepole pine resource in Washington and Oregon falls into the "high" or "very high" hazard class; on one Nation-al Forest, however, there is an adequate mosaic of age classes to spur management personnel to utilize the system to set cutting priorities. A Canadian risk-rating system for the mountain pine beetle in lodgepole pine is also available and is based on the classical tree vigor approach; the extent of its use was not known, however (Gene Amman, personal communication).

Management of second-growth ponderosa pine to reduce losses from the mountain pine beetle involves reducing basal area through intermediate cuts (both precommercial and commercial). Thinning programs have been conducted in Pacific Northwest second-growth ponderosa pine for the past 20 years as a standard silvicultural treatment (Paul Buffam, personal communication). Gene Amman (personal communication) reports that the hazard-rating system developed by Sartwell (1971) for eastern Oregon is being used successfully in Montana and Idaho. But it obviously needs modification for application to other geographical areas such as southern Utah, where site quality sharply influences the basal area criterion. Another system, tailored for application to the Black Hills of South Dakota (Stevens et al. 1980), will be tested extensively by FPM personnel in 1980 (Gene Amman, personal communication). In Montana, all lodgepole pine stands have been risk-rated through the use of photo interpretation and timber type maps (Pierce, personal communication).

Regional variations are also evident in the hazard rating for southern pine beetle (SPB) developed under the ESPBRAP. For example, landform influences beetle activity more in east Texas than elsewhere in the South. Soil conditions, which in turn influence the incidence of littleleaf disease, can be the overriding factor in beetle incidence in the Piedmont of Georgia.

Interestingly, a certain commonality in all hazard ratings for coniferous bark beetles is evident: age, basal area (generally embodying both growth rate and stand density), and site quality predominate in all of the hazard-rating systems. As Gerry Hertel has indicated, several of these systems for SPB are in their first stage of evaluation and use in Arkansas, Georgia, and Texas.

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Of corollary interest, several risk-rating systems for forest diseases have been developed and are implemented in many of the western National Forests and Parks. Most successful are those for dwarf mistletoe and those designed to assess the incidence of root rot in various conifers. The adoption and successful application of these systems has helped to pave the way for more ready acceptance of current systems.

In the Northeast, of considerable interest is the work being completed by Houston and colleagues on rating hardwood stands as to both susceptibility *and*, ultimately, vulnerability to gypsy moth defoliation. These ratings are of particular interest to two groups. The local, State, and Federal pest control people could use the system to sharpen their decision process in the selection of areas to spray, but the vulnerability rating is of particular usefulness to forest industry, where high-value forests could be ranked for expected mortality due to defoliation and treated accordingly. The susceptibility rating system is in the testing stage by FPM. This division of the Forest Service will gather additional data through its plot system to provide the basis for a vulnerability rating system. This system, in turn, will give the forest manager figures on losses that he might expect following defoliation.

The other major pest in the Northeast, the eastern spruce budworm, has been a long-standing subject of investigation, particularly by the Canadians. The knowledge that spruce-fir stands can be classified as to susceptibility and managed to reduce budworm damage has been available for decades. But the mechanical difficulties in translating that knowledge into management action over vast acreages have limited its application.

Dealing with the balsam woolly aphid in Newfoundland and Labrador, Hugh Schooley indicates that a "traditional system" based on evaluation, soil moisture, and age and basal area of balsam fir is frequently used by the Provincial Forest Service and industry to locate areas for stand improvement work. Industry managers have not used the system to dictate harvesting, however, since the forested areas requiring harvesting exceed industry's capacity to carry out such operations.

The information from a risk-rating system based on insect counts and defoliation history is also in use on a year-to-year basis to forecast damage potential from the eastern spruce budworm in Newfoundland. A vulnerability rating for spruce budworm similar to that prepared for the balsam woolly aphid should be available for the Island portion of the Province by mid-1981.

The reduction of Federal support for large-scale spray suppression projects for forest insects in the United States and the increasing emphasis on stand management as a major element of integrated pest management (IPM) for the spruce budworm in Maine are discussed in the final Environmental Impact Statement, "Proposed Cooperative Spruce Budworm Suppression project, Maine 1980." This trend deemphasizing toxicants and stressing IPM will probably continue, and should serve to spur more intensive investigation of alternate--primarily silvicultural--means to reduce long-term damage from various forest pests. Hazard or risk rating will continue to be an important part of those investigations.

Gerry Hertel has tabulated a number of hazard-rating systems currently being implemented to various degrees in the United States. To this list might be added several others that appear to have passed the milestone of technology transfer and are progressing down the road to implementation. These additional risk- or hazard-rating systems include the red oak borer, the Saratoga spittlebug, the pine root collar weevil, Nectria and Hypoxylon on aspen, pine sawflies, white pine weevil, and various budworms on pine in the Lake States, particularly in Michigan.

Bob Heyd, of Michigan, reports their approach to advance risk-rating toward implementation in Michigan. A consortium consisting of the USDA Forest Service, Michigan State University, and the Michigan Department of Natural Resources has joined hands in a common goal to advise forest landowners of the usefulness of the various systems I mentioned earlier. They title their joint effort the Michigan Cooperative Forest Pest Management System. And as might be expected, there is a strong emphasis on preventative management. They have followed the standard approach of conducting workshops to acquaint soil conservationists, consulting foresters, and Michigan State Foresters with the applicability of their pest management system.

An interesting approach by Donley is now in the information-dissemination stage in the States of Pennsylvania, Ohio, Kentucky, and Indiana. His system rates the need for direct intervention to reduce damage by the red oak borer. The rating system is based on the number of attacks per 200 ft^2 of bark sampling area in a random exam of sample trees in the red oak group within the stand. Other studies by Donley have shown the positive impact of reducing borer population in a stand by felling and sectioning infested trees. Again, it is a bit too early to evaluate the acceptance of this rating system.

Potential users of a pest management system can sometimes be obstinate. They

may listen politely and totally ignore your plea or they may greet your presentation with the rejoinder: "A better mouse trap only creates an additional disposal problem!" In addition, they may advance these arguments:

1. The damage has not been severe enough to warrant the cost of implementation (i.e., the product does not warrant the cost of implementation), or

2. The system has not been sufficiently tested to warrant adoption, or

3. The methodology is too complicated or too time consuming and therefore too costly.

4. The system is too hard to understand.

5. The computer program would have to be changed.

Finally, they may exhibit a general resistance to any change.

In anticipating these responses, the research community must recognize certain of its direct responsibilities. First, the model usually does not have to be 95 percent accurate--in many areas a target of 75 percent may be more realistic. An unrealistic level of accuracy may well increase the time and effort necessary to collect the required data, and the method may be rejected for that reason alone.

Cost figures (in terms of wage dollars or hours) are an important factor of any argument for adopting a program. The dollar value of thinning in reducing future damage by SPB, for example, offers a much more convincing argument and perhaps the only effective argument to forest industry where the "bottom line" is King! Unfortunately, such studies have not been an integral part of the standard Forest Service research program in the past.

The successful hazard- or risk-rating systems being utilized to date have been those which are relatively simple to apply, require a minimum of measurements, are broadly applicable, and have been shown to be effective in use.

Yesterday's users were the foresters in the field; many of tomorrow's users will be a different breed. Application of the interrelated and, therefore, more complex models of insect population and stand dynamics will require input of data collected in the field, and often collected by the user. These data will feed the various models; the output will be utilized by FPM personnel, National Forest administrators, State pest control specialists, or perhaps the woodlands manager for a wood-using industry. These users must understand the fundamental concepts of the proposed pest management system and the models which are an integral part of that system. Knowledge and understanding breed trust--if trust is warranted--and support for the system. We have progressed beyond simply rating the risk of insect attack; we are moving toward a comprehensive pest management system or ultimately to a resource management system in which forest pests are one of a number of management concerns.

The development of complex models involving risk-rating will include not only the "risk" or likelihood of outbreak, but also the risk of attack (susceptibility), the risk of damage (vulnerability), together with the risks associated with the selection of various control methods. These elements are all interrelated and integral parts of a complete risk-rating system. An example of such a system, although some portions are still in the formulation and testing stage, is that developed for the Douglas-fir tussock moth (DFTM).

Larry Freeman, of FPM, Pacific Southwest Region, reported (personal communication) that the Region

> developed a system to classify sites and stands as to susceptible or nonsusceptible as part of our participation in the Expanded DFTM RD&A Program. A preliminary version of the system has been used informally to facilitate our DFTM detection activities using the DFTM pheromone. We are currently in the final stages of developing and implementing the system formally, including a discriminate interactive model that predicts the likelihood of a stand being susceptible to DFTM, for use by land managers and entomologists.

I spoke at some length with Barry Malac, Union Camp Corporation, Savannah, Georgia, regarding his evaluation of the current and future applicability of hazard-rating systems in the South. Union Camp is not currently employing any of the hazard-rating systems now available for such forest pests as *Fomes annosus* (FA), fusiform rust, pales weevil, or SPB. Barry indicated that their new Integrated Pest Management Specialist, John Godbee, has been assigned the task of looking at all of these rating systems with the objective of recommending the adoption of those systems most useful and practical. Barry expressed his feeling that few of these risk-rating procedures had been proven in the field (a point with which I disagree, in the case of FA and SPB).

In discussion of the future of thinning by the pulpwood industry in the South, where hazard ratings for SPB, FA, and to a lesser extent improvement cuts for fusiform rust apply, Sharon Miller, Chesapeake Corporation, West Point, Virginia, reiterated widespread support of the concept of

thinning by the pulpwood industry throughout the South (if rotation age exceeds 25 years). He pointed out, however, that no one has been successful in developing cost-effective mechanical equipment to carry out the task. The lesson is clear: proven applicability, effectiveness, or usefulness of a system cannot ensure its widespread adoption unless it can be implemented economically.

In the West, as all of my correspondents indicate, it will be years before all high-risk stands are actually under proper management, since actual application is limited by the orderly progression of cutting schedules.

There is a definite future for risk-rating systems. The impending shortage of both pulpwood and sawtimber, evident from the recent forest surveys in many areas of the South, has produced a positive response from the forest industry. Their initial action has been to organize an effort to increase reforestation activities, to offset the annual losses of pine acreage. The next logical step should be a realization that intensive forest management will help to reduce future losses to pine bark beetles and other forest pests.

Mandated long-term planning for public forest land should be an important vehicle for integrating pest management considerations such as risk ratings into overall management considerations on the National Forests and eventually on State and private forest land.

Advanced technology, including aerial photography and satellite imagery, is available to help classify stands over large areas. Computer management, which is increasingly utilized by companies with large holdings, should permit easy integration of stand management guidelines for various forest pests.

Forest industry is cooperating to a larger extent in supporting research efforts at various universities, primarily through cooperatives. Witness the effort currently underway to enlist industry participation in an integrated pest management center at the University of Florida. Ten to 15 companies are expected to contribute tangible support to that project.

Many of the rating systems will soon be available or are already in place. The future looks bright--2 p.m. may not, after all, be too early to start to convince the vast world out there of the value of our existence!

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LITERATURE CITED

Amman, G. D., M. D. McGregor, D. B. Cahill, and W. H. Klein. 1977. Guidelines for reducing losses to the mountain pine beetle in unmanaged stands in the Rocky Mountains. 19 p. U.S. Dep. Agric., Gen. Tech. Rep. INT-36. Intermountain For. Range Exp. Stn., Ogden, Utah.

Keen, F. P. 1936. Relative susceptibility of ponderosa pine to bark beetle attack. J. For. 34:919-927.

Miller, J. M., and F. P. Keen. 1960. Biology and control of the western pine beetle. 381 p. U.S. Dep. Agric. For. Serv., Misc. Publ. 800.

Salman, K. A., and J. W. Bongberg. 1942. Logging high risk trees to control insects in the pine stands of northeastern California. J. For. 40:533-539.

Sartwell, C. 1971. Thinning ponderosa pine to prevent outbreaks of the mountain pine beetle. *In* Precommercial thinning of coastal and intermountain forests in the Pacific Northwest. D. M. Baumgartner, ed. p. 41-52. Wash. State Univ. Coop. Ext. Serv., Pullman.

Smith, R. H., B. E. Wickman, R. C. Hall, C. J. DeMars, and G. T. Ferrell. 1981. The California Pine Risk-Rating System: its development, use, and relationship to other systems. *In* Hazard-rating systems in forest insect pest management: symposium proceedings. [Athens, Ga., July 1980.] R. L. Hedden, S. J. Barras, and J. E. Coster, coords. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-27.

Stevens, R. E., W. F. McCambridge, and C. B. Edmister. 1980. Risk rating guide for mountain pine beetle in Black Hills ponderosa pine. 2 p. U.S. Dep. Agric. For. Serv., Res. Note RM-385. Rocky Mountain For. Range. Exp. Stn., Missoula, Mont.

SEEDLING DEBARKING WEEVILS: A SITE HAZARD-RATING SYSTEM CASE HISTORY

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Abstract.--Seedling debarking weevils (*Hylobius pales* Herbst and *Pachylobius picivorus* Germar) were found to be a serious threat to the establishment of new pine plantations in Arkansas and southeast Oklahoma. A seedling protection strategy was developed in the early 1970's which utilized a site hazard-rating system based on logging date, and a choice of chemical protection treatments. While effective in many areas, the treatments did not provide sufficient protection in southeast Oklahoma, as revealed by a statistical evaluation of historical records on over 300 plantations. As a result of this analysis, we developed a logistic model that predicted the probability of a plantation receiving significant weevil activity based on the number of weeks between logging and April 1. Further analysis is underway to define the relationship of spring weevil damage to fall seedling mortality. Revised weevil protection guidelines are proposed based on the above analyses.

INTRODUCTION

Beginning in about 1970, Weyerhaeuser Company initiated a plan to practice intensive forestry on 1.5 million acres of recently purchased land in Arkansas and southeast Oklahoma. Previous to 1970, this land had been under an uneven-age management system, where pine was selectively harvested from the mixed pine-hardwood stands. Since continuation of the selective-logging system would ultimately result in establishment of pure stands of lowvalue hardwoods, the company decided to begin converting immediately to a high-value, even-age pine management regime where economically feasible. This was accomplished in most cases by utilizing a system of clearcutting, site preparation, and planting of loblolly pine (*Pinus taeda* L.).

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While the establishment of young, even-age pine plantations was generally successful, it became immediately apparent that significant first-year seedling mortality was being caused by seedling debarking weevils (*Hylobius pales* Herbst and *Pachylobius picivorus* Germar), hereafter referred to as weevils. In this paper we will present (1) the weevil problem in relation to Weyerhaeuser's forest management activities, (2) development of a seedling protection strategy utilizing a site hazard-rating system and insecticide protective treatments, (3) evaluation of the protection strategy, (4) revised seedling protection strategies, and (5) future needs.

THE PROBLEM

The life history and damage potential of reproduction weevils has long been recognized (Carter 1916, Peirson 1921). Following the development of artificial regeneration systems in the South in the 1950's, various investigators discovered more specific information on the relationship of weevils to intensive forestry (Doggett 1977, Speers and Rauschenberger 1971, Speers 1974, Thatcher 1960).

Weevils are principally a problem of even-age pine management systems. The insects are attracted into freshly cut areas, where they breed in the roots of pine stumps and in buried slash. Upon emerging, both the original adults and their offspring feed on the bark of newly planted pine seedlings. The seedlings are killed once they have been completely girdled.

There is a wide variation in the susceptibility of new pine plantations to damage by weevils. In general, areas logged in the winter and spring months are safe for planting the following winter, because weevils are no longer present in great abundance. However, areas logged in the summer are moderately susceptible to attack, and severe seedling mortality can occur in plantations established in the winter after fall logging (Doggett et al. 1977, Frazier 1969, Speers and Rauschenberger 1971, Speers 1974, Thatcher 1960). In the case of summer or fall logging, original adults and some emerging weevil progeny are still present on the site to feed on seedlings planted the following winter and spring. Surveys on Weyerhaeuser lands in Arkansas and Oklahoma in the early 1970's indicated the following average weevil-caused seedling mortality on

plantations established the winter after site preparation during the following seasons: spring--6 percent, summer--20 percent, fall--58 percent.

Based on the apparent relationship between logging date and subsequent weevil-caused seedling mortality, investigators made several attempts to develop a site hazard-rating system. However, efforts to predict weevil-caused seedling mortality at the end of the first growing season based on earlier trap catches or other site variables have had only marginal success. Frazier (1969) found no significant correlation in Virginia between subsequent weevil-caused seedling mortality and type of site preparation, pine basal area cut, acreage cut, month of logging, or weevil trap catches immediately after logging. Doggett et al. (1977) found direct relationships in North Carolina between weevil-caused seedling mortality and (1) amount of pine pushed down during site preparation, and (2) weevil trap catches following planting.

Thus, prior to 1978, site hazard-rating systems for weevils existed in a qualitative sense. But quantitative estimates of weevil damage based on month of logging, pine volume removed, or other site or management variables were nonexistent.

STRATEGIES FOR SEEDLING PROTECTION

When it became obvious in the early 1970's that we would have a severe weevil problem in many of our new plantations, several options for controlling weevil damage were proposed: (1) disperse harvest areas, (2) restrict harvesting to spring months, (3) delay planting, (4) use seedling protective treatments. After a careful economic analysis, we determined that if an effective seedling protection treatment could be developed, that approach had the greatest potential benefit.

Utilizing a combination of laboratory screening and field testing techniques, we developed three different chemical protection treatments and registered them for use: (1) a clay slurry carbofuran preplant seedling dip (Walstad et al. 1973), (2) a carbofuran granular treatment applied at time of planting (Nord et al. 1975, 1978), and (3) a chlorpyrifos foliar postplanting spray (Walstad and Nord 1975). Both the carbofuran and chlorpyrifos insecticides afforded significant protection. In most cases the chlorpyrifos foliar spray (2 percent a.i.) provided the best control, followed by the carbofuran granular treatment (1 to 2 g a.i. per seedling), and the carbofuran clay slurry seedling dip (1 percent a.i.).

With the availability of the above new tools, we designed a seedling protection strategy based on relative susceptibility of sites and performances of the various seedling protection treatments (Walstad and Nord 1975). Planting sites were classified according to weevil hazard based on logging and site preparation dates. "Cold" areas, where hazard was low due to early logging and site preparation, required no treatment. Since hazard was low, planting of "cold" areas was scheduled in the winter ahead of the more hazardous "warm" and "hot" areas, which were planted later to minimize the time the seedlings were exposed to weevil feeding.

Seedlings in "hot" areas required maximum protection so they were treated with carbofuran granules or chlorpyrifos foliar sprays. Because of the longer residual life of these treatments, "hot" areas were planted in February or early March. "Warm" areas were planted in March with seedlings treated by the carbofuran clay slurry root dip method. Unanticipated outbreaks, resulting from adjacent logging or other disturbances, were controlled with the chlorpyrifos foliar spray.

Weyerhaeuser Company foresters have been using these prescriptions across the South since 1975. We developed a "dribble bar" for applying carbofuran granules as the seedlings are planted, and we used a conventional backpack sprayer for applying the chlorpyrifos foliar sprays. The carbofuran clay slurry root dip was applied at Weyerhaeuser Company nurseries. Detailed safety precautions and periodic training sessions help prevent any accidents in handling these materials.

EVALUATION OF PROTECTION STRATEGIES

Between 1975 and 1980, the above prescriptions appeared to do an excellent job of preventing significant weevil-caused mortality. But it became apparent in Weyerhaeuser's Oklahoma Region (where weevil damage was always the most severe) that some of the prescriptions were not providing sufficient protection. The result of this problem was that significant acreages had to receive remedial chlorpyrifos sprays. This prompted a review of the efficacy of the weevil prescriptions in southeastern Oklahoma.

Data on over 300 Oklahoma plantations planted from 1975 to 1978 were used to evaluate the weevil control program and to characterize plantations requiring postplanting applications of chlorpyrifos. Since all plantations in the region were monitored intensively (at least monthly) for weevil damage and received chlorpyrifos applications only when 10 percent or more of the seedlings showed signs of damage, the necessity for remedial treatments

automatically marked a plantation as an area of significant weevil activity. Plantations requiring chlorpyrifos remedial treatments were compared and contrasted with those that did not, for the following variables: site preparation methods; date and quality of slash burn; seed source; planting stock lift week and storage duration; logging, site preparation, and planting dates; insecticide treatment(s) used; number of acres logged; and stocking level.

Contingency tables were used to display the distribution of plantations that required chlorpyrifos treatments over the various variables and to examine relationships between variables. We tested relationships observed in the tables for statistical significance with χ^2 tests, and we evaluated in a logistic model significant variables related to the need for chlorpyrifos treatments as predictors of the probability of weevil activity (PWA).

The major variable found to be associated with weevil activity as measured by the incidence of chlorpyrifos treatment was the number of weeks between logging and the following April 1 (WLA). This was a measure of the interval between logging and date of significant spring weevil activity. Several other variables were associated with chlorpyrifos treatment (date of site preparation, planting, etc.) but were not independent of WLA. Therefore, they were not included in the model. The final function derived was

$$PWA = \frac{1}{1 + e^{(-1.84 + 0.074\ WLA)}}$$

The probability of any plantation having sufficient weevil activity to warrant chlorpyrifos treatment increased as the number of weeks between logging and spring weevil activity (April 1) decreased (table 1).

Analysis indicated that the incidence of chlorpyrifos treatment was not related to site preparation method, ripping, duration of logging activity, lift week and storage duration of planting stock, time interval between ripping and planting, or time interval between site preparation and planting. There were no significant differences in proportions of plantations treated with chlorpyrifos among the three site preparation methods most frequently used in the Oklahoma Region--KG and pile, tree crush, and roll and chop. Similar results were observed between ripped and nonripped settings.

The χ^2 test indicated that chlorpyrifos incidence was related to burn quality ($p = 0.05$). However, chlorpyrifos incidence and burn quality were both related to WLA ($p = 0.05$). The log likelihood χ^2 test indicated that if allowance were made for WLA, there was no significant relationship between chlorpyrifos treatment and burn quality ($p = 0.05$).

Perhaps the most important result of this analysis indicated that preplant carbofuran treatments (both granules and clay slurry seedling dips) did not reduce the proportion of plantations receiving chlorpyrifos postplant remedial treatments. This remained true even if the interval between logging and weevil activity was taken into account. Thus, based on this analysis, neither the carbofuran slurry nor the granular treatments were providing sufficient protection from weevil damage in the Oklahoma Region.

REVISED GUIDELINES

With the above information in hand, we were able to revise the weevil protection guidelines for Oklahoma to make them more effective. We made several important recommendations as a result of the above analysis:

1. Where possible, areas logged after July 1 should be held over for one year before planting.

2. Seedlings planted on land logged between June and August can be protected by treating with carbofuran seedling dip and delaying planting until mid-March or later.

3. If areas logged after September 1 must be planted the same year, the area should be monitored intensively (weekly) for weevil activity and treated with chlorpyrifos when significant weevil activity (10 percent of seedlings damaged) is observed.

4. Carbofuran granules should be eliminated as a protection treatment.

FUTURE RESEARCH

While the above analyses allowed us to estimate spring weevil activity based on logging dates, we needed additional information to complete the revised weevil hazard-rating system. The above analysis was performed on data from operational plantations, all of which received reme-

Table 1.--Probability of weevil activity (PWA), as indicated by the need for chlorpyrifos treatment, by weeks between logging and spring weevil activity (April 1) (WLA)

WLA	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
PWA	.86	.81	.75	.67	.58	.49	.40	.31	.24	.18	.13	.09	.06	.04	.03

dial sprays when significant weevil damage was detected. Therefore, it was impossible to develop seedling mortality curves from these data.

Uncertainty remained, however, regarding the relationship of early spring weevil damage to end-of-season seedling mortality. This was a critical piece of information since the decision to apply or not apply the chlorpyrifos treatment depended upon it. Therefore, in 1979, a series of research plots was established to determine (1) the relationship of spring weevil damage to seedling mortality in October, and (2) the function which defines the relationship between the number of weeks between logging and April 1 (WLA) and October seedling survival. These studies are currently being analyzed. Hopefully, they will allow us to further refine the guidelines and to establish a solid threshold level of weevil damage on which to base decisions regarding remedial spray treatments.

LITERATURE CITED

Carter, E. E. 1916. *Hylobius pales* as a factor in the reproduction of conifers of New England. Soc. Am. Foresters Proc. 11(3):297-307.

Doggett, C. A., C. R. Grady, H. J. Green, M. B. Kunselman, H. Layman, and S. Taylor. 1977. Seedling debarking weevils in North Carolina. 10 p. N.C. For. Serv., Res. Note 31. Office of Forest Resources, Raleigh, N.C.

Nord, J. C., T. H. Flavell, W. D. Pepper, and H. F. Layman. 1975. Field test of chlorpyrifos and carbofuran to control weevils that debark pine seedlings. 7 p. U.S. Dep. Agric. For. Serv., Res. Note SE-226. Southeast. For. Exp. Stn., Asheville, N.C.

Nord, J. C., T. H. Flavell, W. D. Pepper, and H. F. Layman. 1978. Field test of four insecticides for control of pales and pitch-eating weevils in first-year pine plantations. 9 p. U.S. Dep. Agric. For. Serv., Res. Note SE-255. Southeast. For. Exp. Stn., Asheville, N.C.

irson, H. B. 1921. The life history and control of pales weevil. 33 p. Harvard For. Bull. 3. Cambridge, Mass.

Speers, C. F. 1971. Pales and pitch-eating weevils: ratio and period of attack in the South. 5 p. U.S. Dep. Agric. For. Serv., Res. Note SE-156. Southeast. For. Exp. Stn., Asheville, N.C.

Speers, C. F. 1974. Pales and pitch-eating weevils: development in relation to time pines are cut in the Southeast. 7 p. U.S. Dep. Agric. For. Serv., Res. Note SE-207. Southeast For. Exp. Stn., Asheville, N.C.

Speers, C. F., and J. L. Rauschenberger. 1971. Pales weevil. 6 p. U.S. Dep. Agric. For. Serv., For. Pest Leafl. 104.

Thatcher, R. C. 1960. Influence of the pitch-eating weevil on pine regeneration in east Texas. For. Sci. 6(4): 354-361.

Walstad, J. D., J. B. Hart, Jr., and S. C. Cade. 1973. Carbofuran clay root dip protects loblolly pine seedlings from debarking weevils. J. Econ. Entomol. 66(5):1219-1220.

Walstad, J. D., and J. C. Nord. 1975. Applied aspects of pales weevil control. Down to Earth 31(1):8-12.

PREDICTING SEEDLING DEBARKING WEEVIL HAZARD IN NORTH CAROLINA

Coleman A. Doggett[1]

Adult seedling debarking weevils, primarily pales weevil (*Hylobius pales* Herbst.) and pitch-eating weevil (*Pachylobius picivorus* Germar), cause serious damage to pine seedlings in North Carolina by feeding on the bark of stems and roots of seedlings. When feeding is heavy, the seedlings are girdled and killed (Beal and McClintick 1943). Damage occurs only when seedlings are planted on areas where pines have recently been cut or killed in some other manner. The extent of seedling damage on these areas is related to the amount of pine material involved and the time interval between cutting or killing pine material and planting (Doggett et al. 1977).

The potential for weevil damage in North Carolina has increased significantly since tree planting on a wide scale was initiated. This increased potential is the result of changing silvicultural practices.

Prior to the middle 1950's, most tree planting in North Carolina was done in open fields. Methods for preparing and planting wooded sites were not well developed at that time, so very little planting was done on cutover tracts. Open field planting on private, nonindustrial lands accelerated tremendously from 1956-60, when the Federal conservation reserve, or soil bank program, was initiated. Over 106,000 acres of open land were planted in trees under this program, primarily to remove cropland from production. As might be expected, since no pine material was involved in open field planting, debarking weevils were not a factor in stand establishment.

Beginning in the mid-fifties and early sixties, numerous intensive site preparation methods were developed. These allowed the preparation of wooded land for planting. One site-preparation method was chemical treatment of residual trees followed by planting. A second was the mechanical destruction of residual trees with heavy equipment followed by planting. Heavy equipment for this type of work is as varied as the imaginations of foresters and engineers. Some of the equipment used included discs, K-G blades, rolling choppers, large drag chains, and tree crushers. Since woodland previously in pine was often site prepared, seedling debarking weevil problems became a serious consideration in stand establishment.

Although intensive mechanical site preparation is still the standard, particularly on industrial lands, we are beginning to see a change. This change is being brought about by the high cost of intensive preparation, the unavailability of heavy equipment, and by environmental objections. Instead of intensive mechanical methods, we are beginning to see more of what we term extensive site preparation. A good example of an extensive method is to plant immediately after a clearcut or a total tree chipping, without site preparation. Another common method is simply to clearcut, burn, and plant. These methods generally require planting soon after cutting to minimize competition from hardwood sprouts. Consequently, a very high hazard exists for weevil damage. I foresee an increase in the use of extensive site preparation methods in the Southeast with attendant potential for increased weevil damage. Therefore, it is becoming essential for the forest manager to predict weevil hazard on planting sites.

DEVELOPING A SYSTEM FOR PREDICTING WEEVIL HAZARD

One important observation in developing a hazard-prediction system was the recognition that a time factor was involved in weevil damage. If there is sufficient delay between pine harvest or other mortality causes and subsequent planting, there will be no weevil damage. A planting delay of 2 to 3 years was recommended in the British Isles for *Hylobius abietis* (British Forestry Commission 1955) and in the northeastern United States (Potts 1955). Spears (1956) recommended that in the southeastern United States, either a 1-year delay be observed between cutting or fire and planting, or treated seedlings be used. After insecticidal and trapping studies in Coastal Plain North Carolina in 1966-67, Grady and Layman (1967) recommended that seedlings planted on areas from which any pine was cut after June 1 be top-dipped in DDT.

The June 1 cutoff date, with DDT treatment of all seedlings planted on areas cut after that date, was successfully used until the registration of DDT was cancelled in 1974. When DDT was banned, a well-developed site preparation program for private, nonindustrial lands was underway. Approximately 12,000 acres were being site prepared annually, and 4,000 acres were being burned and planted.

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A high proportion of these acres had some pine material removed. In order to keep the site preparation and planting program operational, a more refined system was developed. This system continued the use of the June 1 cutoff date but included, in addition to the cutoff date, the amount of pine material involved. The pine material parameters used were based on a field study conducted by Tex Kunselman in 1964-65 (Doggett et al. 1977). The system was released for use by the North Carolina Forest Service field personnel in 1974 and has been used operationally since that date.

THE NORTH CAROLINA WEEVIL HAZARD-RATING SYSTEM

1. If no pine has been cut from an area to be planted, there will be no weevil problem.

2. If a pine stand is cut prior to June 1 and the area will be planted during the following winter, there will be no weevil problem.

3. If 3 cords of pine or less are cut from an area or pushed down during site preparation after June 1, losses should be less than 5 percent if the area is planted during the following winter.

4. If 5 to 10 cords/acre of pine are cut or pushed down during site preparation, losses may be up to 25 percent if the area is planted the following winter.

5. If over 10 cords of pulpwood or 5,000 fbm of sawtimber are cut or pushed down during site preparation after June 1, either use treated seedlings or postpone planting and plant seedlings next year.

Occasionally, a high-hazard area is inadvertently planted with untreated seedlings. When this occurs and seedlings begin to die, we can predict mortality at the end of the season. This is done by a series of curves (fig. 1) that predict seedling mortality in July based upon mortality in any preceding month. If an unacceptable mortality rate is predicted, the seedlings are chemically treated. If projected mortality will still leave an acceptable stand, no control action is taken.

Luckily, after the DDT ban, there was only one year when no chemicals were registered for use against weevils. Three chemicals are now registered: Dursban® (chlorpyrifos) is registered as an infield spray; Imidan® (phosmet) as a topdip; and Furadan® (carbofuran), a systemic, both as a clay slurry root dip and placed around the base of the seedling.

I would like to mention that in the Southeast there is another hazard-rating system in use, which was developed by Walstad and Nord (1975). Their system, which is based on logging and site preparation dates, has been used primarily on industrial lands. Table 1 summarizes this system and treatment recommendations.

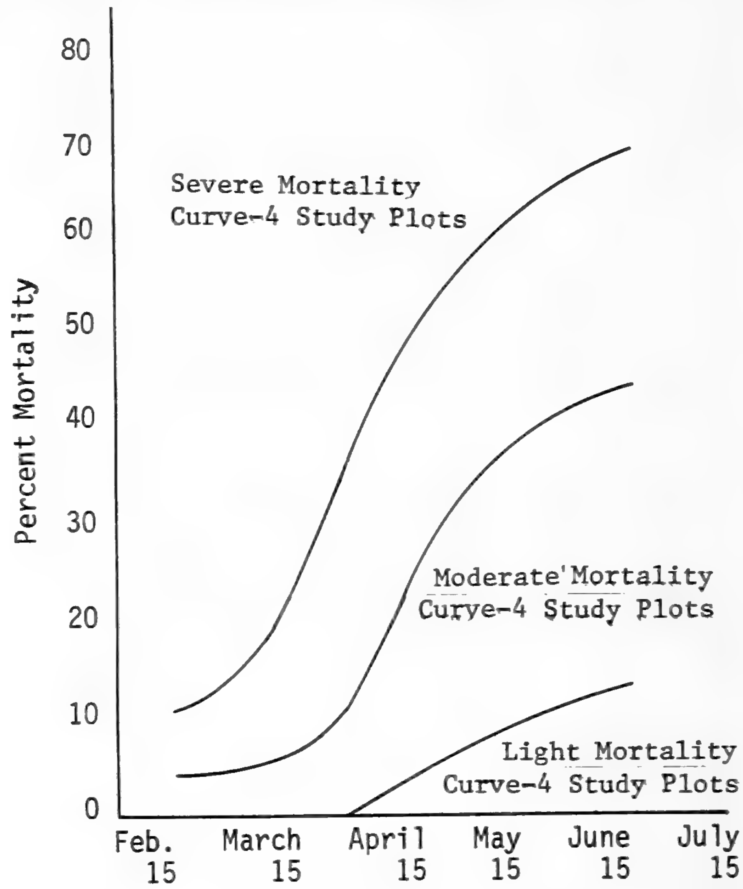

Figure 1.--Pine seedling mortality, Columbus County, N.C., 1964-71.

RESULTS, RECOMMENDATIONS, AND NEEDS

After six seasons of using the hazard-rating system on hundreds of tracts, I am confident that we can predict problem areas. I am not satisfied that we can predict the magnitude of loss within these problem areas. Some areas that we class as high-risk may have only moderate damage; in others, weevil populations may be so great that seedlings are overwhelmed and killed even when treated seedlings are used. More study is needed to enable us to pinpoint these abnormally high population sites.

We also are beginning to encounter operational problems in planting because of lack of control over the tree planter. Even though treated seedlings are recommended by our forester, and are available at our nurseries, the tree planter may not plant treated seedlings. We are beginning to see scattered instances of this occurring. It may be necessary to check all tracts that are supposed to be planted with treated seedlings, either during planting or several weeks after, to be sure that treated seedlings were used.

Table 1.--Reproduction weevil hazard rating for pine lands based on logging and site preparation date with recommended control

Hazard rating	Logging date	Site preparation date	Planting date	Treatment
Cold	Winter-spring	Spring-summer	Dec.-Feb.	None
Warm	Summer	Summer-fall	Feb.-March	Furadan 10G Imidan 50W + extender Dursban M
			March	Furadan 4F
Hot	Fall	Fall	Feb.-March	Furadan 10G Imidan 50W + extender Dursban M
Unexpected damage				Dursban M Imidan 50W + extender (Sprays)

I strongly feel that Southwide impact data is needed to get an accurate assessment of present losses and to determine the effect of changing silvicultural practices (fewer trees per acre planted, extensive site preparation, total tree harvesting). Seedling survival checks for forestry purposes are made routinely in the fall or winter. Seedlings killed by weevils during the previous spring and summer have often deteriorated by the time survival checks are made so that it is impossible to accurately assign reasons for mortality. Therefore, we cannot rely on routine forestry survival checks to identify weevil damage. A special effort must be made to collect data on weevil impact. A cooperative effort will be underway this year between the USDA Forest Service, private companies, and State agencies to try to get a better idea of weevil impact.

We are beginning to operationally plant containerized seedlings throughout the year. Because of this, we need to be able to forecast accurately the length of time weevils will stay in a cutover area. We plan to collect this information as soon as time permits.

LITERATURE CITED

Beal, J. A., and K. B. McClintick. 1943. The pales weevil in southern pines. J. Econ. Entomol. 36:792-794.

British Forestry Commission. 1952. The large pine weevil. 8 p. Brit. For. Comm., Leafl. 1. London.

Doggett, C. A., C. R. Grady, H. J. Green, M. B. Kunselman, H. Layman, and S. Taylor. 1977. Seedling debarking weevils in North Carolina. 15 p. North Carolina For. Serv., For. Note 31. No. Carolina Dep. Nat. & Econ. Res., Raleigh.

Potts, S. F. 1955. Use of sprays to control the pales weevil. 2 p. U.S. Dep. Agric. For. Serv., Res. Note 51. Northeast. For. Exp. Stn., Upper Darby, Pa.

Speers, C. F. 1956. Pales weevil control with insecticides: first year results. 2 p. U.S. Dep. Agric. For. Serv., Res. Note 96. Southeast. For. Exp. Stn., Asheville, N.C.

Walstad, J. D., and J. C. Nord. 1975. Applied aspects of pales weevil control. Down to Earth 31:8-12.

THE INFLUENCE OF RED PINE SITE QUALITY ON DAMAGE BY THE EUROPEAN PINE SHOOT MOTH

Herman John Heikkenen[1]

INTRODUCTION

Since the introduction of the European pine shoot moth (*Rhyacionia buoliana* [Schiff]), the most seriously damaged host has been red pine (*Pinus resinosa* Ait.). Although entire plantations have been attacked, variations in the amount of tree damage have been observed. This study explores the possibility that differences in the amount of damage may be attributable to the tree (Heikkenen 1963).[2]

The dating of old attacks by the shoot moth made possible the simultaneous comparison of damage within and between stands, the evaluation of the causes of variations, and the recognition of dominant control factors. The correlation between damage to trees and various site factors was tested through multiple-regression analysis of data collected in Wexford and Cadillac Counties in Michigan. Soil moisture deficits proved to be the most important site condition associated with severe damage to red pine by the shoot moth.

LITERATURE REVIEW

The first study of host-site quality interactions on the shoot moth was made in Belgium by Voûte and Walenkamp (1946), who showed a direct association of past outbreaks with dry Julys during the period 1893-1940. Their findings were supported by Neugebauer (1952) in Germany. Voûte and Walenkamp believed that low tree resistance was the result of an unfavorable moisture situation; damage to Scots pine (*Pinus sylvestris* L.) was associated with very dry or deeply tilled sites, or sites with a high water table.

In North America the possibility that site quality may affect tree resistance is suggested by variations in damage reported in Connecticut by Friend and West (1933) and in Michigan by Rudolph (1949). However, they attributed differences in damage to the slow dispersal of the moths, rather than to any condition of the site for red pine.

DEVELOPMENT OF SITE HYPOTHESIS

Dating Damage

The needles, buds, and shoots of the red pine provide the shoot moth with food and shelter during the larval and pupal stages. After the needle-mining period, the early-instar larva mines a newly formed bud beginning in late June and early July. The result is summer injury. After overwintering in the bud, the late-instar larva becomes active about the middle of April. Spring injury occurs when the larva bores into fresh buds or elongating shoots. The insect pupates within the bud or shoot and the adult emerges after 2 or 3 weeks. The flight period lasts for about 1 month, beginning in mid-June.

Infested buds can be detected by resin exudates, frass, entrance and emergence holes, and empty pupal skins. Shoot moth attack during past seasons can be identified by mined buds, reduction in the number of branches per whorl, and stem deformities (Heikkenen 1960).

The damage to the tree's form or growth varies with the position of the attacked bud within the bud cluster, the time of year the bud or shoot was attacked, the extent of the insect's feeding, and the subsequent development of the bud or shoot. The following types of stem injuries are characteristic of shoot moth attack (Heikkenen and Miller 1960).

Pruning

The lateral buds in the terminal bud cluster may be destroyed either in the summer or in the spring. The result is, in effect, a pruning of lateral branches. This reduction of branches in the whorl can range from one to all. If all lateral buds are killed, the bud scale scars will remain until bark sloughing occurs. The loss of the lateral buds produces no crook in the main stem.

Crook and Fork

In some instances the terminal bud is destroyed. If undamaged lateral buds

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[2] My deepest appreciation to Doctors S. A. Graham, F. B. Knight, S. H. Spurr, and R. Zahner for their guidance and my education in forestry.

are present, a lateral shoot usually continues height growth. The result may be a crook in the main stem. The loss of form will depend on the degree of offset and the number of lateral shoots that continue height growth. When two or more laterals continue height growth, a forked stem is the result.

Posthorn, Bush and Spike

During the spring, late-instar larvae occasionally feed upon the side of the developing terminal bud or shoot. If feeding stops before the shoot is killed, the injured leader often bends at the point of attack. If the injured shoot continues to grow, a characteristic "posthorn" is formed.

When all buds on the terminal shoot are destroyed, adventitious buds may form. If these buds are destroyed, additional adventitious buds may form; the growth resembles a bush. A lateral below the "bush" usually assumes dominance.

When adventitious buds do not develop and the insect attack kills the terminal, the dead top is termed a spike.

Not all of the stem deformities in red pine are caused by the shoot moth. Similar injury may be inflicted by other insects, mammals, birds, disease, weather, or man. However, these injuries are usually distinguishable.

Damage to the main stem in the form of pruning, crooks, and forking can be dated by the number of years represented by the internodes between the terminal and the point of injury. Damage in the form of posthorns, bushes, and spike tops can be dated by counting the internodes on a relatively undamaged lateral branch below the point of injury. Care should be taken to avoid counting false internodes created by summer shoots. When all branches are badly damaged, a specific injury can be dated by counting the annual rings just below the point of injury.

Variations in Damage

During the spring of 1958, Miller discovered a sharply delineated area of lightly damaged red pine within a severely damaged plantation (Miller 1967). The dating of past attacks revealed all trees. had been attacked for an equal period of time. Height growth of the severely damaged trees was stopped in 1958 yet had continued in the lightly damaged trees. Simi lar variations in damage within plantations were observed during the summer of 1958 in both Michigan and Ontario, Canada. In all cases the lightly and severely damaged red pine had been attaked for an equal length of time.

Plantations of severely damaged red pine infested annually for more than 13 years were also found; the shoot moth had reduced the trees to bushes. It is important to note that examination of apparently normal plantations near severely damaged plantations revealed that the insect was present. Reductions in the number of branches per whorl showed that damage varied during specific years. Although these trees were still infested, normal height growth had continued.

Plantations were also observed that had recovered from severe damage. An outbreak occurred during 1946-47 in red pine plantations on the Stinchfield Forest of the University of Michigan. More than 100 live larvae (spring count) were on the average tree (Melton 1947). Although serious tree damage resulted, the trees resumed normal height growth in 1948.

To obtain more evidence of tree recovery I visited the plantations where the first outbreak on red pine had occurred in the 1930's: the Eli Whitney Forest of Yale University (Friend and West 1933). Dr. R. B. Friend identified the original plantations in the field during October 1958.[3] The trees had recovered and continued height growth in a normal manner.

The Ohio plantations where Miller and Neiswander (1955) had studied the shoot moth were also reexamined in 1958. The past damage and subsequent recovery were obvious. During the outbreak the number of branches per whorl had dropped to less than two during 1952-54. But in 1955-57 there were more than three branches per whorl.

Causes of Variation

Oviposition.--The wide variation in tree damage within and between plantations could be attributed to either oviposition or larval mortality. Past studies attributed variations to the insect; the moth was believed to be a poor flyer, having a slow rate of spread and a tendency to reinfest the same tree (Friend and West 1933, Miller and Neiswander 1955). However in 1957 considerable flight was shown by Green et al. (1957) with the use of a

[3] I am especially indebted to Dr. Friend for his advice and help in the beginning of this study.

radioactive tracer. Green and Pointing (1962) then proved the insect was a strong flyer.[4]

But evidence based on actual egg counts was needed. In three young red pine plantations having "islands" of lightly damaged trees scattered among severely damaged trees, Miller and I laid out adjacent, paired 1/10-acre plots--one in the lightly damaged, the other in the heavily damaged trees. Oviposition was compared in terms of the mean number of eggs on the mean tree. The number of eggs found on both the damaged and lightly damaged trees was more than sufficient to provide high larval populations. The results strongly suggested that variations in tree damage were not attributable to differences in oviposition.

Lethal temperature.--Previous American studies of the shoot moth stressed two mortality factors: cold weather and parasites. Lethal cold temperature was initially considered the primary cause of mortality after West (1936) found that -18°F killed the overwintering larvae. However, severe tree damage continued to be reported from areas where -18°F occurred almost every year (Batzer and Benjamin 1954, Beckwith 1957).

The explanation for severe damage where lethal cold temperature occurred was found by Green (1962b) to be due to the insulating effect of snow:

> . . . the European pine shoot moth could exist with little mortality due to freezing almost anywhere throughout the North American distribution of red pine providing that snow cover during the winter months is sufficient to cover infested buds to a depth of eight inches.

However, the possibility exists that if lethal temperatures occurred in areas of little or no snow cover, a shoot moth population could be destroyed. This is believed to have happened to the shoot moth outbreak on the Stinchfield Forest of the University of Michigan in the winter of 1947-48 (Williams 1957).

Warm weather.--After studying the Connecticut plantations, it was apparent that in addition to the severe outbreak of the early 1930's there were minor outbreaks in 1935-36, 1943-45, 1949-50, and 1955-57. These years were associated with hot, dry summers. A study of weather data also revealed that below-normal summer precipitation and above-normal summer temperatures had occurred during the Ohio outbreak of the early 1950's and the Michigan outbreak of the mid-1950's. These facts suggest that hot, dry summer weather may be associated with annual variations in outbreaks of the shoot moth.

Parasites.--During the shoot moth outbreaks observed, parasites did not exercise effective control; the average rate of parasitism was seldom more than 10 percent. In Ohio, Miller and Neiswander (1955) reported 17 percent, and in Quebec, Béique (1960) found 66 percent. It is highly probable that the sharply delineated areas of lightly damaged trees were searched by parasites.

Stand conditions.--The chances are remote that individual tree differences are the cause of variation in tree damage by the shoot moth. Red pine is well recognized as a uniform phenotype. Genotypic resistance would most likely occur in isolated, individual trees. This has not been the case; variation in the damage was associated with groups of trees.

The influence of stand closure is debatable. Serious damage was observed in closed plantations in Michigan; some were infested prior to closure, others after closure. Crown closure must have occurred in one of the infested plantations studied at Rose Pond by Friend and West (1933, Plates VI, VII). These trees had been planted at a 6 by 6-foot spacing and when first infested had reached a height of 17 feet.

It is very unlikely that the extent of crown closure or individual tree differences are the primary causes of variation in tree damage on adjacent areas.

Site quality.--Measurements of annual height growth in adjacent areas of lightly and severely damaged trees (Ottawa County) revealed that trees had a much greater rate of height growth than the adjacent severely damaged trees, both before and during the outbreak. The sharply delineated areas of slightly damaged trees were associated with a geologic feature--a small dune ridge. Behind the ridge, on soils with impeded drainage, the trees were severely damaged. This plantation was not an isolated case. Rapid height growth and reduced tree damage by the shoot moth were observed in many infested plantations in Michigan, Connecticut, and Ontario.

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[4] The advice and interest of the Canadian forest entomologists, G. W. Green, P. J. Pointing, and J. A. Juillet, is sincerely appreciated. During August 1958 much unpublished information was made available which contributed greatly to the results of this study.

The differences in the rate of height growth of the trees express a variation in site quality, inasmuch as site index is based on stand age and height. In an evenaged red pine plantation, areas having widely different mean heights are ipso facto sites of differing quality. This view in shoot moth research was not unanimously accepted when first proposed.

The association of the growth rate of red pine with tree injury caused by the shoot moth coincided with edaphic features usually associated with site quality. Trees with slow growth and severe damage were often found in areas with severe wind erosion and excessive drainage. Such trees were frequently associated with xerophytic hardwoods. In Connecticut, shallow soils over bedrock were associated with severe damage. Areas of rapidly growing trees were usually in well-drained depressions, the base of slopes, not eroded, and the areas often supported mesophytic hardwoods. Trees in the lightly damaged plantations usually reached breast height within 5 years of planting, and then maintained a mean annual height growth of more than 15 inches (Heikkenen and Miller 1960). However, trees with rapid growth rates were occasionally damaged, especially when growing on shallow soils over bedrock or ground water.

The study of variations in larval mortality in red pine growing on sites of different quality was initiated during the summer of 1958 (Miller 1967). Miller and I observed considerable mortality of early-instar larvae during the needle-mining period in one rapidly growing, lightly damaged red pine plantation. But little larval mortality occurred during this period in nearby slowly growing, severely damaged red pine plantations. We postulated that when red pine was growing on good sites, the needles were somehow capable of reducing the population levels of the shoot moth during the needlemining period of the early-instar larvae.

SITE HYPOTHESIS

The study of Michigan red pine plantations infested by the shoot moth for several years revealed wide variation in tree damage within and between plantations. In some plantations, severe damage to the tree by the shoot moth continued year after year while other infested stands were only slightly injured. Areas of lightly damaged trees were found adjacent to heavily damaged trees. Plantations that had recovered from outbreaks of the shoot moth were also discovered.

What caused these wide variations of tree damage, especially in the adjacent areas of widely differing tree damage? Egg counts showed that oviposition habits were not involved. Observations indicated that soil characteristics, in conjunction with hot, dry summers, were probably associated with the annual variations in shoot moth outbreaks and the differences in tree injury occurring in adjacent areas. Careful consideration was also given to the natural mortality factors (cold temperatures, parasites) previously considered important. However, these factors were not believed to be the direct cause of variations in tree damage in adjacent areas.

Thus I hypothesized that the susceptibility of red pine to shoot moth attack was associated with the internal moisture stress of the tree, resulting from soil water deficiencies during periods of summer drought. The soil water deficit would provide the common demoninator for site comparison. Zahner (1956) developed techniques for this basic measurement of site quality:

> The evaluation of water deficiencies has real meaning when applied under specific conditions. Two variables affect deficiencies: soil and weather conditions. The latter changes with time and place; i.e., from year to year and from one geographic location to another. When time and geographic regions are held constant, it is possible to evaluate water deficiencies of various sites within a region. When a site within a region is held constant, comparisons of deficiencies are possible among years, or even among months. Thus, it is possible to evaluate water deficiencies for many combinations or circumstances . . . .

Differences in tree damage by the shoot moth also vary in time and in place in apparent association with tree growth and soil water deficits. This association was the basis for the hypothesis of this study: the resistance of red pine to attack by the European pine shoot moth is proportionate to site quality as measured by soil water factors.

METHODS

Plot Selection

The primary concern in the selection of the study plots in Ottawa and Wexford Counties, Michigan, was to avoid bias regarding the site quality for red pine and the incidence of tree damage. The plantations sampled were limited to pure old-field, open-grown red pine with spacings ranging from 6 by 6 to 12 by 12 feet, planted between 1940 and 1951. The minimum plantation width was 200 feet. The plots were approximately 1/10 acre in size. In all, 65 plots were examined.

The range of site quality was sampled by selecting an approximately equal number of plantations from each major geologic feature where red pine had been planted--in Ottawa County dune and lake sands, and moraines in Wexford County. To assure a proportionate area sampling, townships having plantations were combined into units and plantations on a given geologic feature were assigned a random number. The first five plantations per "unit" were sampled.

Tree Measurements

On each plot I selected 10 trees by taking 5 alternate trees along a given row from each of two random starting points. The annual periodic height growth (internodal distance) to date of planting was measured to the nearest inch. The diameter (outside bark) was measured to the nearest 1/10 inch at breast height and at 1 ft above the ground. To obtain data on root characteristics, I dug a soil pit beside a selected tree near the plot center. Measurements to the nearest inch were made on the length of the taproot, the mean depth of the majority of roots, and the maximum depth of rooting. Soil profile descriptions were also made.

Tree Damage

Annual damage to the tree by the shoot moth was identified and dated on each of the 10 selected trees (Heikkenen 1960). To evaluate shoot moth damage to the lateral buds, I counted the annual number of branches per whorl. Terminal bud injury was recorded at each node in terms of the number of branches in a fork and/or the presence of a crook, post-horn, bush, or spike (Heikkenen and Miller 1960). When terminal growth was stopped by a bush or spike, continuation of height growth by a lateral was measured.

Tree damage by the shoot moth in a given year reflects the feeding of the larvae in the spring of the current year as well as the feeding during the summer of the previous year. One generation of this insect spans two chronological years. This situation is the same for the tree: buds are formed in the summer and expand the following spring. When a chronological year is given in this study, it includes the summer of the previous year.

Soils Description

Within each plot, a soil pit was dug either to a minimum depth of 6 feet or to a shallower water table or to the maximum depth of rooting. From the bottom of the pit a soil auger was sunk an additional 5 ft wherever possible. The Soil Conservation Service soil scientist in each county made soil profile descriptions and identified the soil series. Included were horizon designation, depth, color (Munsell notations), texture, mottling, and structure. In addition, the depth to water table, structural differences, and free water were measured. Also drainage, relief, slope, horizon irregularities, and class of wind erosion were recorded.

Storage Capacity

The storage capacity of the root zone was determined for each study plot. The root zone was considered to be the maximum depth from the surface that any root developed.

The storage capacity of the root zone was expressed in inches of water. I computed available water in volume of equivalent rainfall by multiplying the weight of soil per unit volume of soil by the weight percent of readily available water. The resulting product was then multiplied by the depth of the corresponding horizon (in inches) to obtain the available water in inches. Because horizons vary in thickness, the data were then converted to the available water in inches per foot of horizon. On each study plot I determined the storage capacity of the root zone by adjusting the actual depth of each horizon by the inches of available water per foot of horizon for the soil series on which the plot occurred.

Precipitation and Temperature

The mean monthly precipitation (expressed in inches) for each county during the period 1939-59 was derived by averaging the precipitation records of five surrounding U.S. Weather Bureau Stations. Similarly, the mean monthly temperature (expressed in average degrees F) for each county was taken from the monthly temperature records of at least three surrounding U.S. Weather Bureau Stations. The selected stations were near the study plots.

Water Deficits

Using Zahner's (1956) procedures, I calculated the water deficit in inches of water for each study plot for each month of the study period (1939-59). The monthly water deficit was found by subtracting the inches of precipitation from the potential evapotranspiration and then adjusting for the water supplied from soil storage. In this study soils were encountered with storage capacities of only 2. Therefore, I had to extrapolate

Zahner's soil storage supply table to include capacities below 6 inches.

The monthly water deficits were also expressed as percentages of the storage capacity--a most useful datum. Inasmuch as the water deficit varies disproportionately with the storage capacity of the root zone, the percentage of storage capacity permits direct comparison of water deficits on soils throughout the range of storage capacities. This percentage is also a more sensitive index of the soil water-plant regime than the absolute water deficit. For example, the difference between potential evapotranspiration and precipitation may be .52 inch of water. A soil with a storage capacity of 2 inches could supply .48 inch, leaving a water deficit of .04 inch. However, 1.52 inches of water remains in the soil. This would be 76 percent of the storage capacity. But a soil with a storage capacity of 8 inches would be able to completely supply the .52 inch difference, with 7.48 inches of water remaining in the soil. This would be 94 percent of the storage capacity. Thus a potential evaoptranspiration demand of .52 inch would reduce a soil with a 2-inch storage capacity to 76 percent, but only reduce to 94 percent a soil with an 8-inch storage capacity.

Statistical Analysis

In the initial stages of the analyses, graphs were drawn comparing the various environmental factors with the amount of shoot moth damage to the trees. These graphs indicated that the factors directly associated with variations in tree damage included the age, height, and growth rate of the tree; depth of rooting; amount of soil moisture; precipitation; and temperature during the months of larval feeding--and/or combinations of these factors. In order to discover which of these factors were exerting the greatest influence, I used various multiple-regression analyses.[5]

An IBM-7070 was utilized to solve the final regression equations. I used a standard program that calculates the regression equations in a series of steps, adding at each step the single most significant independent variable.[6]

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[5] I appreciate the advice, design, and work on the analyses by J. L. Clutter, Biometrics Division, Southeastern Forest Experiment Station, USDA Forest Service; and R. A. Schroeder, Computing Laboratory, Duke University.

[6] Dr. A. - Multiple Regression Analysis (1961), available at the Digital Computing Laboratory, Duke University, Durham, North Carolina.

The dependent variables used to express shoot moth damage were defined as follows:

Y 1: The mean annual number of branches per whorl per plot (×10)[7]

Y 3: The percentage of trees damaged by bushing, posthorns, and/or spikes per year per plot.

The site factors believed to influence shoot moth damage were the soil water deficiencies during the months of larval feeding (expressed as the percentage of storage capacity) for two consecutive insect generations and the tree characteristics of age, height, and rate of growth. These data and their interactions were used as independent variables and were coded per plot as follows:

Current insect generation

X 1: April - % of storage capacity next year
X 2: June - % of storage capacity current year
X 3: July - % of storage capacity current year
X 4: X 2 - X 3

Previous insect generation

X5: April - % of storage capacity current year
X 6: June - % of storage capacity previous year
X 7: July - % of storage capacity previous year
X 8: X 6 - X 7

Tree characteristics

X 9: Age since planting
X10: Mean annual total height (x10)
X11: Mean annual periodic height increment (internodal distance) (x10)

Quadratics

X12: $(X\ 1)^2$
X13: $(X\ 2)^2$
X14: $(X\ 3)^2$
X15: $(X\ 5)^2$
X16: $(X\ 6)^2$
X17: $(X\ 7)^2$
X18: $(X\ 9)^2$
X19: $(X10)^2$ (x100)
X20: $(X11)^2$ (x100)

Temperatures affecting current insect generation

X21: Mean April temperature next year (x10)

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[7] Input data were scaled to range from .1 to 10.

X22: Mean June temperature current year (x10)
X23: Mean July temperature current year (x10)

Temperatures affecting previous insect generation

X24: Mean April temperature current year (x10)
X25: Mean June temperature previous year (x10)
X26: Mean July temperature previous year (x10)

RESULTS

Outbreaks of the shoot moth on red pine were found to be significantly associated with the age and growth rate of the tree, amount of soil moisture within the root zone, and summer temperatures. Tree injury in the form of reductions in the mean annual number of branches per whorl was associated with slowly growing trees, soils with low moisture content, and hot summer temperatures. Severe shoot moth damage resulting in bushing of the tree was also associated with low soil moisture levels and hot summer temperatures. The conclusion is reached that in Ottawa and Wexford Counties, Michigan, *the tree is the primary natural mortality factor influencing populations of the shoot moth.* The tree's resistance to attack by the shoot moth is influenced by the amount of water available within the root zone during the time when the larvae are feeding.

The selected regression equations explain between 60 and 75 percent of the variation in tree damage caused by the shoot moth, with acceptable errors of estimate. In a statistical sense, the null hypothesis is rejected that shoot moth damage is not associated with site quality for red pine.

Branches per Whorl

There is no sharply marked point where damage to the tree begins. However, the arbitrary limit set as an indication of outbreak conditions is when the number of branches per whorl are two or less for one or more years and when stem deformity occurs on more than 40 percent of the trees (Talerico and Heikkenen 1962). It is important to note that reductions in the branches per whorl to two or less occur only when the percentage of the available water storage capacity within the root zone has dropped to approximately 40 percent or less in July.

Ottawa County

In Ottawa County reductions in the mean annual number of branches per whorl (Y1) were associated with these independent variables:

Current insect generation

X 3: July - % of storage capacity current year
X22: June temperature current year

Previous insect generation

X24: April temperature current year
X26: July temperature previous year

Tree characteristics

X 9: Age since planting
X11: Mean annual internodal distance

This predicting equation was selected because additional variables did not materially affect the multiple correlation coefficient or the standard error of the estimate:

$$Y1 = 15.455 + .0152 X 3 - .167 X 9 + .207 X 11 - .087 X 22 - .069 X 24 - .0729 X 26$$

Multiple correlation coefficient (R) = .7789
Coefficient of determination $(R)^2$ = 60.67 %
Standard error of the estimate = .951 branches
F-value (6 and 364 d.f.) = 93.58**

Wexford County

In Wexford County, as in Ottawa County, the attacks by the shoot moth on the lateral buds were also associated with slowly growing trees and low levels of soil moisture. Reductions in the mean annual number of branches per whorl (Y1) were associated with these variables:

Tree characteristics

X 9: Age since planting
X11: Mean annual internodal distance

Soil moisture

X 7: July - % of storage capacity previous year

The selected predicting equation is

$$Y1 = .367 + .027 X 7 - .0987 X 9 \quad .212 X 11$$

Multiple correlation coefficient (R) = .8703
Coefficient of determination $(R)^2$ = 75.74%
Standard error of the estimate = .888 branches
F-value (3 and 227 d.f.) = 236.20**

Again it is important to note that reductions in the number of branches per whorl to two or less occur when the percentage of storage capacity approaches 40 percent or less during July.

Bushing

Very heavy infestations result in the destruction of all buds in the terminal cluster. The result is the development of bushes, spikes, or posthorns. In the statistical analysis, all these types of damage were grouped together and designated as "bushing." When bushing and other stem defects, such as forking, occur on 40 percent of the stems, populations of the shoot moth are considered to have reached outbreak numbers (Talerico and Heikkenen 1962). This type of damage to the trees in Ottawa County is associated with storage capacities of 40 percent or less within the root zone. In Wexford County the amount of bushing was too small to provide a sample of adequate size.

In Ottawa County the percentage of trees annually bushed was associated with these variables:

Current insect generation

X 2: June - % of storage capacity current year
X 3: July - % of storage capacity current year
X 4: X 2 - X 3
X22: June temperature current year

Previous insect generation

X 5: April - % storage capacity current year
X 6: June - % storage capacity previous year
X 7: July - % of storage capacity previous year
X 8: X 6 - X 7

Quadratics

X15: $(X5)^2$
X16: $(X6)^2$

This predicting equation was selected:

$$Y3 = 106.855 - .254\ X\ 2 - .644\ X\ 3 + .0069\ X\ 4 - 2.138\ X\ 5 - 1.687\ X\ 6 - .725\ X\ 7 + .008\ X\ 8 + .0151\ X\ 15 + .0111\ X\ 16 + .819\ X\ 22$$

Multiple correlation coefficient (R) = .8252
Coefficient of determination $(R)^2$ = 68.10%
Standard error of the estimate = 15.690%
F-value (10 and 360 d.f.) = 76.81**

Hazardous Sites

Outbreaks of the shoot moth in Michigan are possible only when the storage capacity within the root zone is reduced to 40 percent or less during the summer feeding period of the larvae. Root zones with storage capacities of less than 2 inches are reduced below 40 percent in all but the coolest and wettest summers. On these areas red pine damage may be expected year after year. When the storage capacity of the root zone is approximately 4 inches, reductions below 40 percent occur during summers of average or below-average precipitation. If the storage capacity is approximately 6 inches, tree damage by the shoot moth can occur only during extreme droughts. *Shoot moth damage has not occurred on soils with a storage capacity of 8 or more inches in Ottawa and Wexford Counties, Michigan.* If free water is continuously available, as when a ground water capillary fringe extends into the root zone, the tree is not damaged by the shoot moth regardless of the storage capacity of the root zone.

Storage Capacities

The storage capacities can be predicted for the following soil series in Ottawa and Wexford Counties, Michigan, if the maximum depth of rooting is known:

1. AuGres
2. Saugatuck
3. Rubicon
4. Kalkaska

When the storage capacity of the root zone (Y) is the dependent variable and the maximum depth of rooting, in inches, is the independent variable (X):

$$Y = 6.311\ (\log_{10}X - 5.981)$$

Correlation coefficient (R) = .9381
Coefficient of determination $(R)^2$ = 88.00%
Standard error of estimate = .67 inches
F - value (1 and 47 d.f.) = 344.88**

Depth of Rooting

The maximum depth of red pine roots is influenced by a few dominant factors. From observations on the 65 trees sampled, the dominant factors in the sandy soils appear to be

Age of tree.--From personal observations it appeared that the maximum depth of rooting could be reached within 5 years after planting with the roots descending approximately 1 foot per year in sandy soils.

Degree of erosion.--Six plots were wind-eroded to the "C" horizon on Rubicon, Kalkaska, and Blue Lake soil series. The maximum depth of rooting ranged from 10 to 12 inches ($\bar{X}$ = 11.7 inches). On adjacent noneroded soils, roots descended to greater depths.

Cemented hardpan.--Red pine roots apparently will not penetrate a cemented hardpan. Three soil profiles were examined in the Saugatuck soil series. The roots descended to the proximity of the hardpan but did not penetrate.

Free water.--A total of 23 plots had free water or mottling streaks within 12 feet of the surface. Roots decended to the proximity of the water or mottling, with the exception of the three plots with cemented hardpans (Saugatuck). The depth of rooting (Y) can be predicted if the depth of free water or mottling (X) is known. The three plots with cemented hardpans were not used to determine the depth of rooting to free water.

$$Y = .942\ X - 8.321$$
Correlation coefficient (R) = .9013
Coefficient of determination $(R)^2$ = 81.23%
Standard error of estimate = 11.02 inches
F-value (1 and 18 d.f.) = 77.91**

Structural differences.--There is an association between the occurrence of texture-gravel bands and the depth of rooting. When multiple bands occur, the deeper lying band is associated with the maximum depth of rooting. This phenomenon was observed on 31 plots.

$$Y = 36.616 + .463\ X$$

Correlation coefficient (R) = .4813
Coefficient of determination $(R)^2$ = 23.17%
Standard error of estimate = 14.70 inches
F-value (1 and 28 d.f.) = 8.44**

Overburden.--An overburden (wind-deposited soil) occurred on nine plots. In all but one plot rooting depth was closely associated with the sequence of dominant factors: hard-pan, free water, and texture-gravel bands.

Pure sand.--Only two plots were "pure" sand--that is, there was no wind erosion, hardpan, mottling, free water, or textural-gravel bands within 12 feet of the surface. One plot occurred on a Rubicon sand and one on a Kalkaska sand. The maximum rooting depths were 24 and 36 inches on these plots.

SILVICULTURAL CONTROL

To prevent perennial shoot moth damage to red pine in Michigan, the tree should not be planted on soils where the root zone holds less than 2 inches of water. On these soils the drought limits for red pine in shoot moth-infested areas are exceeded nearly every year. This condition occurs in Ottawa and Wexford Counties on (1) sandy soils, wind-eroded to the "C" horizon, and (2) sandy soils where the root zone is restricted to 18 inches by a hardpan or free water. Conditions in (2) are found on the AuGres and Saugatuck soil series.

Occasionally severe outbreaks of the shoot moth occur during droughts on soils capable of storing more than 2 but less than 6 inches of water within the root zone; this occurs when the roots do not reach a depth of more than 78 inches. Shallow rooting occurs where a fluctuating water table is within six feet of the surface and texture-gravel bands do not occur within 10 feet of the surface. Damage can be avoided by not planting red pine on these soils.

Other pine species are more resistant to the shoot moth than red pine. In Ottawa County, three broad susceptibility classes exist for eight pine species (Miller and Heikkenen 1959). The most susceptible species is red pine. The low susceptibility class includes white, jack, Virginia, and pitch pines. On sites with water-holding capacities of less than 4 inches, the best species for Ottawa and Wexford Counties, Michigan, is probably jack pine.

LITERATURE CITED

Batzer, H. O., and D. M. Benjamin. 1954. Cold temperature tolerance of the European pine shoot moth in lower Michigan. J. Econ. Entomol. 47:801-803.

Beckwith, L. C. 1957. Weather station records not an accurate guide to temperatures lethal to the shoot moth. U.S. Dep. Agric. For. Serv., Tech. Note 508. Lake States For. Exp. Stn., St. Paul, Minn.

Béique, R. 1960. The importance of the European pine shoot moth, *Rhyacionia buoliana* (Schiff.) in Quebec City and vicinity. Can. Entomol. 92:858-862.

Friend, R. B., and A. S. West. 1933. The European pine shoot moth (*Rhyacionia buoliana* (Schiff.) with special reference to its occurrence in the Eli Whitney Forest. Yale Sch. For. Bull. 37.

Green, G. W. 1962a. Flight and dispersal of the European pine shoot moth, *Rhyacionia buoliana* (Schiff.). I. Factors affecting flight, and the flight potential of females. Can. Entomol. 94:282-299.

Green, G. W. 1962b. Low winter temperatures and the European pine shoot moth, *Rhyacionia buoliana* (Schiff.) in Ontario. Can. Entomol. 94:314-336.

Green, G. W., W. F. Baldwin, and C. R. Sullivan. 1957. The use of radioactive cobalt in studies of the dispersal of

adult females of the European pine shoot moth, *Rhyacionia buoliana* (Schiff.). Can. Entomol. 89:379-383.

Green, G. W. and P. J. Pointing. 1962. Flight and dispersal of the European pine shoot moth, *Rhyacionia buoliana* (Schiff.) in Ontario. Can. Entomol. 94:314-336.

Heikkenen, H. J. 1960. The identification and dating of past attacks of the European pine shoot moth on red pine. J. For. 58:380-384.

Heikkenen, H. J. 1963. Influence of site and other factors on damage by the European pine shoot moth. Ph.D. diss., Sch. Nat. Res., Univ. Mich. 137 p.

Heikkenen, H. J., and W. E. Miller. 1960. European pine shoot moth damage as related to red pine growth. 12 p. U.S. Dep. Agric. For. Serv., Lake States For. Exp. Stn. Pap. 83.

Melton, R. E. 1947. A study of the European pine shoot moth in a young red pine plantation in southern Michigan. Master's thesis, Sch. Nat. Res., Univ. Mich.

Miller, W. E. 1960. The European pine shoot moth: relationship between proportion of trees infested and number of insects per tree. J. For. 58:647-648.

Miller, W. E. 1967. The European pine shoot moth: ecology and control in the Lake States. For. Sci. Monogr. 14.

Miller, W. E., and H. J. Heikkenen. 1959. The relative susceptibility of eight pine species to European pine shoot moth attack in Michigan. J. For. 57: 912-914.

Miller, W. E., and R. B. Neiswander. 1955. Biology and control of the European pine shoot moth. Ohio Agric. Exp. Stn. Res. Bull. 760.

Neugebauer, W. 1952. Die bekampfung des kieferntriebwicklers. Forstarchiv 23: 152-165: (G.g.).

Rudolf, P. O. 1949. Red pine and the European pine shoot moth in southern Michigan. Pap. Mich. Acad. Sci. 35:61-67.

Talerico, R. L., and H. J. Heikkenen. 1962. Stem injury to young red pine by the European pine shoot moth. J. For. 60: 403-406.

Voûte, A. D., and J.F.G.M. Walenkamp. 1946. De oorzaak van het ooptreden van gradaties van de dennenloutrups (*Evetria buoliana* Schiff.) ende mogelijkheid deze te voorkomen. Mededeel. Com. Bestud. Insectpl. Bossch. 14: (Fl.,e.).

West, A. S., Jr. 1936. Winter mortality of larvae of the European pine shoot moth, *Rhyacionia buoliana* (Schiff.), in Connecticut. Ann. Entomol. Soc. Am. 29: 438-448.

Williams, C. B., Jr. 1957. Spring emergence of the European pine shoot moth, *Rhyacionia buoliana* (Schiff), in Stinchfield Woods. Master's thesis, School. Nat. Resour., Univ. Michigan, Ann Arbor.

Zahner, R. 1956. Evaluating summer water deficiencies. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Occas. Pap. 150. [Discontinued Southern Station series.]

AN INTEGRATED APPROACH FOR ASSESSING SPRUCE BUDWORM DAMAGE, AND DEVELOPING A HAZARD-RATING SYSTEM AND STAND MODELS FOR SPRUCE-FIR STANDS IN MICHIGAN'S UPPER PENINSULA

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Abstract.--During 1977-79, we developed an overall plan for our 1978-83 study on the impact and damage assessment of the spruce budworm on spruce-fir forests in the Ottawa and Hiawatha National Forests in Michigan's Upper Peninsula. The long-term objectives of this study are development of techniques for sampling impact, quantification of impact, development of a hazard-rating system, and development of stand models. This paper presents a description of our approach for designing long-term damage assessment studies along with comments on our sampling scheme for the Michigan Impact Plot System. We also discuss the development of additional short-term (1- to 2-year) studies to collect detailed information on specific types of impact that presently are not available from our impact study plot system. A hazard-rating system and stand models will be developed during the last 3 years of our study using information available from the Michigan Impact Plot System and other specialized studies.

INTRODUCTION

During 1977-79, we developed an overall plan for our long-term integrated study on the impact of the spruce budworm, *Choristoneura fumiferana* (Clemens), on spruce-fir stands in Michigan's Upper Peninsula. The purpose of this paper is to describe this integrated approach.

CURRENT SPRUCE BUDWORM OUTBREAK IN MICHIGAN

The most recent spruce budworm outbreak in the Lake States began in the 1960's. Mortality of balsam fir was first reported in the eastern part of Michigan's Upper Peninsula (i.e., Mackinac and Chippewa Counties) in 1971 (Hastings and Renlund 1976). Currently, most of the spruce-fir stands in Michigan are under attack. Heyd and McKeague (1979) reported that over 100,000 ha of private and State land in the Upper Peninsula were under attack. Our observations on Federal lands in Michigan's Upper Peninsula during 1978-80 indicate that there is severe defoliation and significant tree mortality. However, the damage varies from light defoliation to nearly 100 percent tree mortality.

OVERALL STUDY DESIGN

The steps in our overall study design for 1977-84 were outlined by Witter et al. (1980) as follows:

1. Review of existing literature and discussion of proposed research ideas with other researchers and land managers (1977, 1978).

2. Determination of long-term and short-term objectives (1977-83).

3. Development of study plans (1977, 1978) and submission of grant proposals (yearly, 1978-83).

4. Establishment (1978, 1979) and evaluation (1978-82) of the Michigan Impact Plot System.

5. Development (1979-81) of storage capabilities, computer programs, and mapping routines for the impact data collected during 1978-82.

6. Design and implementation of additional studies to meet the objectives of this project (1979, 1980).

7. Analysis of data and development of final products (1979-83).

8. Determination of new priorities and finalization of studies for the next field season (winter prior to each field season).

9. Participation in working and user group meetings (1978-84).

10. Publication of techniques and results of studies (1979-84).

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Interaction Between Researchers and Managers

Key points for a successful research program include a thorough review of existing literature and discussion of research ideas with other researchers and land managers.

We reviewed the literature available on the spruce budworm (McKnight 1968; U.S. Department of Agriculture 1975, 1976, 1978). We then visited and discussed our proposed research with other researchers and pest managers who had worked on spruce budworm impact and damage assessment. Next we discussed our proposed studies with land managers representing various interest groups in the Lake States, such as the USDA Forest Service, Michigan Department of Natural Resources, and private industry.

The USDA Combined Forest Pest Program for the gypsy moth, Douglas-fir tussock moth, and southern pine beetle and the CANUSA Spruce Budworms Program have developed planning techniques to meet specific objectives within a limited time by using the Adapted Convergence Technique for Agricultural Research (Shea and Bayley 1977). In essence, this technique identifies needs and priorities for the specific forest pest management program (e.g., spruce budworm) and organizes them in a structured manner. The final product of this overall planning process is a well-defined activity schedule (Brookes et al. 1978).

The Combined Forest Pest Program and the CANUSA Spruce Budworms Program have helped the individual researcher to focus on existing literature (Jennings et al. 1979) and to keep abreast of current and proposed research by requiring all funded investigators to meet annually and discuss needed areas of coordination, gaps in data being collected, current research, and recommendations made to program management for future changes.

Determining Long- and Short-Term Objectives

After review and discussion of existing knowledge, the objectives of the study must be determined. The long-term objectives of our 1978-83 spruce budworm study are (1) development of techniques for sampling impact, (2) quantification of impact, (3) development of a hazard-rating system for spruce-fir stands in Michigan's Upper Peninsula, and (4) development of stand models for susceptible and less susceptible stands in the Ottawa National Forest.

We have found that determination of more specific objectives for each field season is useful in setting short-term goals and priorities. Having the short-term goals defined makes the development of grant proposals easier because many grants are for 1 year and/or are reviewed annually.

Our specific objective for the 1978-79 study was establishment of the Michigan Impact Plot System.

Our specific objectives for the 1979-80 studies were (1) evaluation of the 108 ground sampling units established in 1978 and the establishment and evaluation of 28 additional ground sampling units; (2) development of storage capabilities, computer programs, and mapping routines for the damage assessment information gathered during 1978-82; (3) determination of the number and size of ground sampling units required to accurately estimate tree mortality; and (4) determination of the accuracy of tree mortality estimates obtained using remote sensing techniques.

Our specific objectives for the 1980-81 studies are (1) evaluation of the ground sampling units in the Michigan Impact Plot System, (2) evaluation of regeneration present in spruce-fir stands, (3) determination of the accuracy with which remote sensing techniques can provide estimates of the parameters that appear most predictive of hazard, and (4) development of guidelines for constructing hazard-rating systems for spruce-fir stands.

Study Plans and Grant Proposals

Many grant proposals are hastily written just prior to submission, and those turned down by granting agencies are often poorly prepared. The major problem with such proposals is that the investigator did not spend the time necessary to develop a structured study plan. In our estimation, the key points in developing study plans and writing grant proposals are (1) knowing the needs and priorities of the granting agency, (2) developing clear, concise objectives, (3) allocating the time needed to develop a study plan and/or grant proposal, (4) developing the methodology necessary to meet the objectives of the study, (5) developing a realistic time schedule for the proposed study, and (6) developing a detailed budget that permits the investigator to meet study objectives and also allows the granting agency to review proposed costs.

We urge administrators of granting agencies, interested researchers, and forest managers to continue stressing the need for long-term studies relating to damage assessment, hazard rating, and silviculture. Waters and Stark (1980) reported that "forest pest management has a sound conceptual, methodological, and technical foundation for implementation as an

integral part of forest resource management planning and operations." However, they note, "in reality, no forest pest management systems, in this sense, are yet in operation" and "for pest management to be an integral part of forest management, a look-ahead policy must displace the wait and see policy, and pest monitoring and treatment studies must be fully incorporated into the overall planning and decision process." For this to occur, additional emphasis must be placed on monitoring the impact of forest pests.

For our study, we developed the overall study plan during 1977 and 1978. We submit individual grant proposals on a yearly or multiple-year basis depending on funding sources.

Establishing and Evaluating the Michigan Impact Plot System

An impact study plot system of 136 ground sampling units is now established on the Ottawa and Hiawatha National Forests in Michigan's Upper Peninsula. One hundred eight ground sampling units were established and evaluated in 1978. During 1979, an additional 28 ground sampling units were established and 136 evaluated. In 1980, all 136 ground sampling units were evaluated.

Mog and Witter (1979) and Witter et al. (1980) briefly described the sampling units being used in the Michigan Impact Plot System as (1) primary sampling unit (PSU)--a forest compartment, (2) secondary sampling unit (SSU)--a spruce-fir stand, and (3) tertiary sampling unit (TSU)--circular plots of various radii. The PSU's and SSU's were weighted according to their acreages of spruce-fir and then selected at random from each National Forest. The SSU was divided into two approximately equal parts, and TSU's were randomly located within each of both halves of the stand. A TSU is one of the three circular plots of 0.02, 0.04, and 0.08 ha that were established around a single, fixed plot center. The particular circular plot used depends on the parameter being measured and evaluated. The ground sampling unit is the three concentric circular plots located around a single, fixed plot center. The sampling scheme used is an adaptation of a multistage cluster sampling technique.

A description of the field techniques we are using to assess the impact of the spruce budworm was presented by Mog and Witter (1979). During 1978-82, the following parameters will be evaluated once each year for all ground sampling units: sapling count, budworm feeding on saplings, tree species, d.b.h., crown position, tree condition, tree height, crown condition, defoliation ranking, and tree mortality. Information on increment growth, stand age, and site classification will be obtained for all ground sampling units during 1979 or 1980. We will reevaluate the ground sampling units in 1981 and 1982.

Computer Techniques

Most of the computer programs, storage capabilities, and mapping routines needed for analysis and presentation of the damage assessment data will be completed by late 1980. We will continue to refine these programs during 1981.

We wrote and tested an error-checking routine that detects missing data and errors in coding and key punching the field data, and it is in use. Our computer routine that prepares a facsimile tally sheet is used for data validation and for remeasurement purposes. Two new statistical packages that generate descriptive statistics for the various parameters by plot and by stand are in use. We have completed a program to calculate annual and cumulative changes for the various stand parameters. We are presently working on an additional statistical package to calculate descriptive statistics for the forest districts and national forests, and a mapping routine for presentation of various stand information.

Additional Studies

Much of the data needed to meet the overall objectives of this study is obtained from the Michigan Impact Plot System. However, we also needed additional information from specialized studies of a shorter duration (i.e., 1 to 3 years).

A. Sampling Size Study (1979).

During the summer of 1979, Karpinski and Witter conducted a study to determine the number and size of ground sampling units required to quantify tree mortality accurately in stands infested with the spruce budworm. From all stands being studied in the Ottawa National Forest, we selected six stands with light to moderate defoliation and six stands with moderate to severe defoliation during 1978. Six plot centers were located at random in each of the 12 stands. Concentric circular plots of 0.02, 0.04, and 0.08 ha and a rectangular plot of 0.40 ha were established around each plot center. In all the circular plots, the tree species, d.b.h., and tree condition were recorded for all spruce and fir trees having a d.b.h. of 11.6 cm or greater. Field crews determined tree height, crown position, crown condition, and tree defoliation

ranking for trees on the 0.02- and 0.04-ha plots. For the 0.40-ha rectangular plots, all trees 11.6 cm d.b.h. or greater were tallied as alive or dead, and identified as being fir, spruce, other conifers, or hardwoods. The accuracy of the stand estimates for tree mortality, number of stems per acre, and basal area of fir was compared by plot size and by number of replicated plots within each stand.

B. Remote Sensing (1979, 1980)

During 1979 and 1980, McCarthy, Olson, Bergelin, and Witter are conducting studies to determine the accuracy with which remote sensing techniques can provide estimates of parameters that appear most predictive of hazard in spruce-fir stands. An Olympus OM-1 camera with a 50- or 100-mm lens, haze filter, and motor drive is used to take Ektachrome (ASA 64 or 200) photographs. We photographed stands of spruce-fir from the air at scales of approximately 1:2400, 1:4800, and 1:7200. The photographs are taken primarily between 9 and 11 a.m., from either a Cessna 150 or 182 aircraft during July or August. A crown map is made for each area photographed, by drawing in the tree crowns that appear on the aerial photographs. Using the aerial photograph, we identified trees as fir, spruce, other conifers, or hardwoods. The fir and spruce are rated as alive or dead and given a defoliation ranking. The results obtained using the aerial photographs are compared with those obtained from ground data. McCarthy et al. (1981) described the large-scale, small-format aerial photographic technique used in 1979 to assess spruce budworm damage. They reported that average tree condition estimates can be obtained from color imagery at a scale of 1:4800 with greater than 90 percent accuracy. During 1980, our remote sensing studies are concentrating on methods to increase accuracy of separating spruce from fir, increase accuracy of tree mortality estimates, and to measure parameters used to estimate volume such as tree height, crown closure, crown area, and nearest neighbor.

C. Growth Increment (1979 and 1980)

During 1979 and 1980, we are determining stand age and gathering information on increment growth for all ground sampling units in the Michigan Impact Plot System. A total of 16 increment cores per stand, 8 per ground sampling unit, were obtained. In the laboratory, the amount of increment growth on a yearly basis over the previous 15 years will be determined.

D. Ecological Site Classification (1979-81)

Spurr and Barnes (1980) reviewed multiple-factor methods of site classification which have been employed in Europe for over 50 years and in Canada during the last 30 years. During 1980-81, with the assistance of B. V. Barnes of the University of Michigan, we will be assigning an ecological site classification unit to each of the ground sampling units in the Michigan Impact Plot System. The ecological site classification scheme incorporates factors such as topography, drainage, aspect, depth of organic layers, soil pH and texture, and indicator plant species.

E. Regeneration (1980)

During summer 1980, Lynch and Witter are determining the kind and amount of regeneration present in spruce-fir stands. The regeneration study is being conducted on 12 spruce-fir stands in the Ottawa National Forest (four each in light, moderate, and severely defoliated stands). Four 0.40-ha blocks (40 × 100 m) are being established in each stand. Each 0.40-ha block is subdivided into ten 0.04-ha blocks. Within each 0.04-ha block, 10 milacre quadrats (2 m^2) are located at random. The milacre is the basic sampling unit. Four hundred milacre quadrats will be evaluated for each stand.

The numbers of fir, spruce, and hardwood seedlings are being tallied separately for each milacre plot. Seedlings are being tallied by 15-cm height classes from ground level to 45 cm and by 30-cm height classes from 60 to 240 cm. The data from the regeneration study will be used to determine the impact of the spruce budworm on spruce and fir regeneration in the Ottawa National Forest and to develop stand models for spruce-fir stands in the western part of Michigan's Upper Peninsula.

Analysis of Data and Development of Final Products

Data analysis is an ongoing process throughout our study. Techniques for forest damage assessment, a hazard-rating system, and stand models for spruce-fir stands are the major products being developed in our study. The development of certain techniques for forest damage assessment has already been reported (Mog and Witter 1979, McCarthy et al. 1981) and other techniques will be published throughout the study.

A hazard-rating system for the spruce budworm in Michigan's Upper Peninsula will be developed during 1980-83. A preliminary review of the literature has shown

that there is no complete list of the various parameters affecting hazard rating, nor is their relative importance known. We do know that the character of the forest strongly influences the development of spruce budworm outbreaks, both in terms of susceptibility of a stand to attack and vulnerability of a stand under attack. Over the last 35 years, investigators attempting to identify and quantify tree mortality resulting from spruce budworm attack have found correlations between a number of stand characteristics and damage. Relevant stand characteristics include species composition; percent BA of fir, of spruce, and of nonhost species; volume of fir per unit area; tree height; stand density, age, vigor, size, and structure; topography; and intensity and duration of outbreak (Westveld 1945 and 1954, Balch 1946, McLintock 1948 and 1949, Morris and Bishop 1951, Graham 1956, Bean and Batzer 1956, Batzer 1969 and 1973, van Raalte 1972).

A number of hazard-rating systems predict the susceptibility and/or vulnerability of spruce-fir stands to the spruce budworm. These hazard rating systems have not been universally accepted. It has been noted that they do not have high predictive accuracy throughout the insect's entire range. The limited use of these hazard-rating systems is due in part to extensive forest management practices, little demand for fir and spruce in certain areas, and the unavailability of an accurate hazard-rating system for a specific region or National Forest.

Greater market demand for spruce-fir and more intensive forestry practices have been partially responsible for increased interest in the development and use of hazard-rating systems. Batzer (1969) and Batzer and Hastings (1981) developed a hazard-rating system for spruce-fir stands in Minnesota that relies primarily on basal area of balsam fir at time of spruce budworm attack and on percent of nonhost species.

Information obtained from the Michigan Impact Plot System during 1978-81 will be the basis of our hazard rating system. During winter 1981, a thorough literature review of forest pest hazard rating systems will be concluded. Discussions will be held with the other investigators who are involved with spruce-fir hazard-rating systems. This information will be studied before finalizing the guidelines for our own hazard-rating system. Our goal is to develop a hazard-rating system for spruce-fir stands in Michigan's Upper Peninsula during 1981-82 and to test the system during 1982-83.

Stand models for susceptible and less susceptible spruce-fir stands in the Ottawa National Forest will be developed in 1981-83 from the Michigan Impact Plot System and regeneration study data bases.

Determination of New Priorities and Finalization of Studies for the Next Field Season

It is extremely important to have an overall study plan such as the one discussed in this paper. But there must also be a thorough review of the ongoing project each year. Investigators must determine the needs and priorities for the upcoming field season. New information from the previous year, personnel changes, inflation, travel restrictions, hiring freezes, and budget constraints are some factors that necessitate modification of the overall study design.

Participation in Working and User Group Meetings

It is vital that the principal investigator and other research team members exchange information with other investigators working on similar projects since publication of research findings is often a slow process. Communication with user groups makes the investigators more aware of problems the resource manager may be having.

We have found that required participation at annual CANUSA-East working group meetings is a major asset. The exchange of information with other investigators and discussion of research priorities for the following year has been very beneficial.

Other benefits have been the favorable interest and excellent cooperation we have received from user groups in the Lake States and throughout eastern North America. Our participation in user group meetings in the Upper Peninsula of Michigan (Witter et al. 1979) and a continued discussion of the spruce budworm problem during the last 4 years with forest and pest managers representing private industry, Michigan DNR, and the USFS has kept us aware of their current needs.

Publication of the Techniques and Results of the Studies

Any study which uses a long-term integrated problem-solving approach involves many different investigators, numerous cooperators, and a support staff. However, the ultimate success or failure of any project rests with the timely presentation of the results in publications and technical reports and whether these results and/or products are used by land and pest managers.

FINAL COMMENTS

The objective of this paper was to provide a basic framework for the development of forest insect impact studies. We used our study of the spruce budworm in Michigan's Upper Peninsula as a working example. We hope that discussion of the steps, approaches, and methodology involved in our integrated spruce budworm research studies has been an effective means of presenting this information.

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LITERATURE CITED

Balch, R. E. 1946. The spruce budworm and forest management in the Maritime Provinces. 7 p. Can. Dep. Agric., Div. Entomol. Proc., Pub. 60. Ottawa.

Batzer, H. O. 1969. Forest character and vulnerability of balsam fir to spruce budworm in Minnesota. For. Sci. 15: 17-25.

Batzer, H. O. 1973. Net effect of spruce budworm defoliation on mortality and growth of balsam fir. J. For. 71:34-37.

Batzer, H. O., and A. R. Hastings. 1981. Rating spruce-fir stands for spruce budworm vulnerability in Minnesota. *In* Hazard-rating systems in forest insect pest management: symposium proceedings. [Athens, Ga., July 1981.] R. L. Hedden, S. J. Barras, and J. E. Coster, coords. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-27.

Bean, J. L. and H. O. Batzer. 1956. A spruce budworm risk-rating for spruce-fir types in the Lake States. 2 p. U.S. Dep. Agric. For. Serv., Tech. Note 453. Lake States For. Exp. Stn., St. Paul, Minn.

Brookes, M. H., R. W. Stark, and R. W. Campbell, eds. 1978. The Douglas-fir tussock moth: a synthesis. 331 p. U.S. Dep. Agric., Tech. Bull. 1585.

Graham, S. A. 1956. Hazard rating of stands containing balsam fir according to expected injury by spruce budworm. 2 p. Univ. Mich. School Nat. Resour., Mich. For. Note 13.

Hastings, A. R., and D. W. Renlund. 1976. The budworm situation in the Lake States--1974. pp. 28-37. *In* Proc. Symp. on Spruce Budworm. U.S. Dep. Agric. For. Serv., Misc. Publ. 1327.

Heyd, R. L., and M. McKeague. 1979. An aerial survey of spruce budworm defoliation in the Upper Peninsula of Michigan with management considerations. 5 p. *In* Spruce budworm. Mich. Coop. Forest Pest Management Program Workshop. Vol. 79-1.

Jennings, D. T., F. B. Knight, S. C. Hacker, and M. E. McKnight. 1979. Spruce budworm bibliography. 687 p. Me. Life Sci. Agric. Exp. Stn., Misc. Rep. 213. Orono, Me.

McCarthy, J., C. E. Olson, Jr., and J. A. Witter. 1981. Large scale, small format aerial photography for assessment of spruce-fir stands infested with spruce budworm. J. Photogram. Engineering and Remote Sensing. [In press.]

McKnight, M. E. 1968. A literature review of the spruce, western, and two-year cycle budworms. 35 p. U.S. Dep. Agric. For. Serv., Res. Pap. RM-44. Rocky Mountain For. Exp. Stn., Ft. Collins, Colo.

McLintock, T. F. 1948. Evaluation of tree risk in the spruce fir region of the Northeast. 7 p. U.S. Dep. Agric. For. Serv., Stn. Pap. NE-16. Northeast For. Exp. Stn., Upper Darby, Pa.

McLintock, T. F. 1949. Mapping vulnerability of spruce fir stands in the Northeast to spruce budworm attack. 20 p. U.S. Dep. Agric. For. Serv., Stn. Pap. NE-21. Northeast. For. Exp. Stn., Upper Darby, Pa.

Mog, T. P., and J. A. Witter. 1979. Field techniques for assessing the impact of the spruce budworm (Lepidoptera:

Tortricidae) in Michigan's Upper Peninsula. Great Lakes Entomol. 12: 213-218.

Morris, R. F., and R. L. Bishop. 1951. A method of rapid forest survey for mapping vulnerability to spruce budworm damage. For. Chron. 27:171-178.

Shea, K. R., and N. E. Bayley. 1977. A new approach for planning and coordination of a large project. Proc. 16 World Congr. p. 304-315. Int. Union For. Res. Organ.

Spurr, S. H., and B. V. Barnes. 1980. Forest Ecology. 687 p. John Wiley & Sons, New York.

U.S. Department of Agriculture Forest Service. 1975. Proposed spruce budworms program. 46 p. Washington.

U.S. Department of Agriculture Forest Service. 1976. Draft environmental statement for cooperative spruce budworm supression project--Maine 1976. 137 p. Northeast. Area, State & Private Forestry.

U.S. Department of Agriculture Forest Service. 1978. Final environmental statement cooperative spruce budworm suppression project--Maine, Vermont, and New Hampshire, 1978. 110 p. Northeast Area, State & Private Forestry.

van Raalte, G. C. 1972. Do I have a budworm-supsceptible forest? For. Chron. 48:190-192.

Waters, W. E., and R. W. Stark. 1980. Forest pest management: concept and reality. Ann. Rev. Entomol. 25: 479-509.

Westveld, M. 1945. A suggested method for rating the vulnerability of spruce-fir stands to budworm attack. 4 p. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Westveld, M. 1954. A budworm vigor-resistance classification for spruce and balsam fir. J. For. 52:11-24.

Witter, J. A., C. E. Olson Jr., T. P. Mog, J. McCarthy, and C. Karpinski Jr. 1979. Impact and damage assessment studies on the spruce budworm in Michigan's Upper Peninsula. 5 p. *In* Spruce budworm. Mich. Coop. Forest Pest Management Program Workshop. Vol. 79-1.

Witter, J. A., C. E. Olson Jr., T. P. Mog, J. McCarthy, and C. Karpinski, Jr. 1980. The spruce budworm with emphasis on impact and damage assessment studies in Michigan's Upper Peninsula. Univ. Mich., School Nat. Resour. News 19:5-7.

THE CALIFORNIA PINE RISK-RATING SYSTEM: ITS DEVELOPMENT, USE, AND RELATIONSHIP TO OTHER SYSTEMS

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Abstract.--The California Pine Risk-Rating System provides a method for rating current probability of tree mortality caused largely by western and Jeffrey pine beetle. It was formulated in stands of old-growth, eastside ponderosa and Jeffrey pine in California. Individual trees are risk-rated on easily recognized and classified crown characteristics. When applied to selective logging, it is called sanitation/salvage. Removal of high-risk trees, generally about 15 percent of the stand, recovers the value of trees that would otherwise be lost to insects, and has significantly reduced beetle activity in the area by 80 percent for more than 20 years.

In the mid-1920's efforts were made to find host conditions that cause susceptibility to western pine beetle. No decisive or easily recognized condition was found until Salman turned to crown characteristics of eastside ponderosa pine in the mid-1930's. The California System resulted from this effort. It has become a silvicultural principle for eastside ponderosa and Jeffrey pine in California and Oregon and is applicable to other regions in the West.

Keen Tree Classes preceded and are related to the California System. A penalty system quantifying crown and stem characteristics is a refinement to assist field application of the System. Derivatives of California System include a stand hazard classification for ponderosa and Jeffrey pine in northeastern California and risk-rating systems for red and white fir in northern California.

INTRODUCTION

This paper traces the origins, development, testing, and application of the California Pine Risk-Rating System, called the California System throughout this paper. It is usually called sanitation/salvage when utilized as a logging practice. The System will be described, and examples will be given that first demonstrated its utility as a forest management procedure. A penalty scoring procedure that refines the System and a stand hazard classification that is derived from it will be reviewed along with efforts to extend its use to other forest regions. We conclude with a résumé of research which sought to explain the mode of operation of and causal relationships underlying the risk-rating system.

The California System is applicable primarily to eastside old-growth ponderosa pine (*Pinus ponderosa* Laws.) and Jeffrey pine (*P. jeffreyi* Grev. and Balf.) (fig. 1). Eastside is defined as east of the Sierra Nevada-Cascade crest. It is an individual tree classification system based on an array of easily recognized crown characteristics. Risk, as originally defined and as used in this paper, is basically an estimation of the current probability of a tree being attacked and killed by bark beetles, primarily the western pine beetle (WPB) (*Dendroctonus brevicomis* Lec.) and the Jeffrey pine beetle (JPB) (*D. jeffreyi* Hopk.), and to some extent by the flathead borer (*Melanophila californica* VD).

Figure 1.--Typical stands of eastside ponderosa pine suitable for risk rating.

From an evolutionary and developmental viewpoint it is worthwhile to discuss the Keen Tree Class System along with the California System, since there may be some confusion between the two. Both evolved from the same background experience and had nearly a parallel course of development. From all evidence it appears that the California System might have been par-

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tially derived from the Tree Class System; or at least those who developed the California System were able to benefit from the experience of the Tree Class System.

We chose to organize the review rather strongly around the processes which were involved because these are important aspects for subsequent research and development, and they are often overlooked. Much of the content of our review can be found in a small number of technical reports, particularly in several sections of Miller and Keen (1960). The task was to recheck old reports and publications and, hopefully, to highlight the processes used, to examine the successes and failures, and to record the ideas which were tried during the period of development.

BACKGROUND

Four related developments preceded the California System: (1) studies of tree selection, (2) development of tree classification systems, (3) conduct and analysis of large-scale direct control programs (i.e., directly killing the brood or removing it from the forest) in northeastern California and southern Oregon, and (4) establishment of a small experimental cutting based on tree classification.

Tree selection research was an early effort to determine the nature of trees attacked by WPB. This research was followed by Dunning's Classification, based on tree physiognomy (Dunning 1928), which in turn was modified to produce the Keen Tree Classification System (Keen 1943). All three developments in selection and classification partially reached their objectives, but none was successful in providing a reasonable explanation of selection or an easy and effective system of risk classification. These developments, however, formed a partial basis for the California System. Analysis of large-scale direct control programs, showing uncertainty of their results, established a climate that gave impetus to research on alternative methods of control. The small logging study, based on insect selection criteria, was a key development that led most directly to the California System.

Tree Selection

The origins of many new developments in biology are often lost in the past; and so it seems to be with the California System. Thirty years before it was formalized, there were suggestions, including reports by A. D. Hopkins shortly after 1900, of a preferential habit of attack by bark beetles. But until about 1925 these references were general, sketchy, and based on only casual field observations.

The story really begins in the 1920's, when there was a concerted thrust of research on the basic biology and ecology of the WPB. It was from this work that specific ideas of risk originated. Miller's report (1926b) is a good place to start. In that report of bark beetle losses on plots located on the western slope of the Sierra Nevada, he presented evidence of the preference of WPB for ponderosa pines with slower growth rates. He also found some degree of association between crown characteristics and the incidence of beetle attack, the starting point for thinking of the possible value of crown characteristics as indicators of risk. At about the same time Person (1926) reported on one of the key studies in the development of risk in which he concluded that trees with the smallest crowns were the most susceptible to attack. In fact, he suggested that there is an inverse relationship between crown size and susceptibility to attack. As for population phenomena in relationship to susceptible trees, Person (1928) thought that large numbers of susceptible trees in a stand permit a rapid increase in beetle population resulting in greater probability of epidemic infestations in trees that were not normally susceptible. Person (1931) then theorized that a secondary attraction for beetles is created in and by trees which are easily overcome.

Struble continued the work Person had started on growth rate. The final report (Struble 1942) showed 22 percent of the trees and 28 percent of the volume was killed over a 22-year period. In years of light beetle activity, a decided preference was shown for the slower-growing trees. This preference was less pronounced in years of heavy beetle activity.

From 1925 to 1929 research was expanded to discover the reasons for a tree's relative susceptibility or resistance to beetle attack. The early portion of this work was done near Northfork on the Sierra National Forest; the latter portion was near Buck Creek on the Modoc National Forest. Among the characteristics considered were phloem moisture, bark sugar, phloem electric potential, bark thickness, and resin toxicity. Neither these stem characteristics nor the crown characteristics studied by Miller and Person were found to be decisive. It is worth noting that much of this early research was done in west slope Sierra Nevada ponderosa pine type, an area in which no risk system yet developed has been found applicable. Although these early scientists had the right idea, they were working in the wrong place for demonstrating the risk phenomenon.

Nevertheless, they began a course of action which was to produce the California System. Their research also served as the training ground for many of those who did much of the subsequent studies on the more important bark beetles in the West.

Analysis of Direct Control Programs

Direct control is killing immature brood or beetles in, or as they emerge from, infested trees--before brood emergence. From 1910 to 1925 numerous direct control programs were conducted for WPB in California and southern Oregon, primarily using the feel-peel-burn procedure.

Craighead (1925) noted this about WPB:

> The theory that killing the broods in a large percentage of the trees will reduce the infestation to just such an extent sounds reasonable. It does not, however, take into consideration the fact that under favorable conditions these insects have extraordinary powers of multiplication and that under these same conditions possibly fewer beetles are required to overcome the resistance of the tree. Even with the most carefully executed work it is rarely possible to treat more than 80 percent of the infestation. The other 20 percent, under optimum conditions for attack and development, might readily offset such a reduction. For some time Mr. Miller has been doubtful of the effectiveness of this method of fighting the western pine beetle. He has stated his objections as follows: (1) This type of control work is expensive, (2) uniformly successful results have not been secured, and (3) the results are not permanent.

Miller (1926a) referred to the WPB/ ponderosa pine relationship:

> In the early studies of this problem the insect itself was regarded as the primary active agent and the host tree was considered only as a passive medium which was attacked indiscriminately. It is now realized that the reactions of the tree must be considered as well as the activities of the beetles, and that the vigor of a tree has much to do with its susceptibility or its resistance to bark beetle attack.

After recounting the work on tree selection, Miller stated that

> these discoveries open up the possibility of reducing losses through logging practice and of taking out most of the susceptible trees in the marking practice on sale areas so as to leave only the more resistant trees for seeding purposes and future cuts.

Finally Craighead et al. (1931) noted that the benefits of direct control of bark beetles, including WPB, were sometimes uncertain and the effects were usually temporary. They asked for research and development on some kind of silvicultural practice to overcome these disadvantages.

It would appear that these three articles represented the attitude and philosophy that fostered research and development on tree classification and risk-rating.

Additional support for the position that the host played a critical role in the dynamics of bark beetle population came from the effects of a natural phenomenon, the cold temperatures of winter 1932-33. These temperatures caused a severe reduction in WPB broods throughout northern California (Miller 1933); yet 2 years later, the outbreak was as extreme and widespread as before the freeze.

Keen and Dunning Tree Classifications

In the late 1920's the research thrust shifted from the west slope of the Sierra Nevada to eastside ponderosa pine in northeast California and southern Oregon, where Keen was conducting annual surveys of areas with persistently heavy bark beetle losses. Early surveys were primarily loss surveys, although some attention was given to crown characteristics of attacked trees. Then, during an epidemic year, Keen added Dunning's (1928) new tree vigor classification to the requirements of the survey; that is, the survey crew placed each attacked tree into one of Dunning's seven classes. The relative abundance of Dunning's seven classes in the unattacked stand was tallied so that the ratio of attacked to unattacked trees could be obtained. This first effort to link attacked trees with Dunning's vigor classes was unsatisfactory, because often as much variation occurred within a Dunning class as between classes.

It was becoming clear, however, that what was described by the vague term "vigor" was a fruitful concept to explore. Keen expanded Dunning's 7 classes into 16 classes. First called bark-beetle susceptibility classes, these were later to become the Keen Tree Classes (fig. 2). Keen (1936) also saw quite clearly what was required for the solution of the bark beetle problem in southern Oregon and northern California:

> . . . one of the first requirements in the solution of the pine beetle problem is a knowledge of what type of tree presents the greatest risk of beetle attack. Once the type of tree most likely to be killed can be recognized with a fair degree of certainty, it is possible to make partial cuttings of beetle-susceptible trees, either for the purpose of salvaging valuable high-risk trees before they are damaged by beetle attack or

for the silvicultural objective of reducing mortality and increasing net growth.

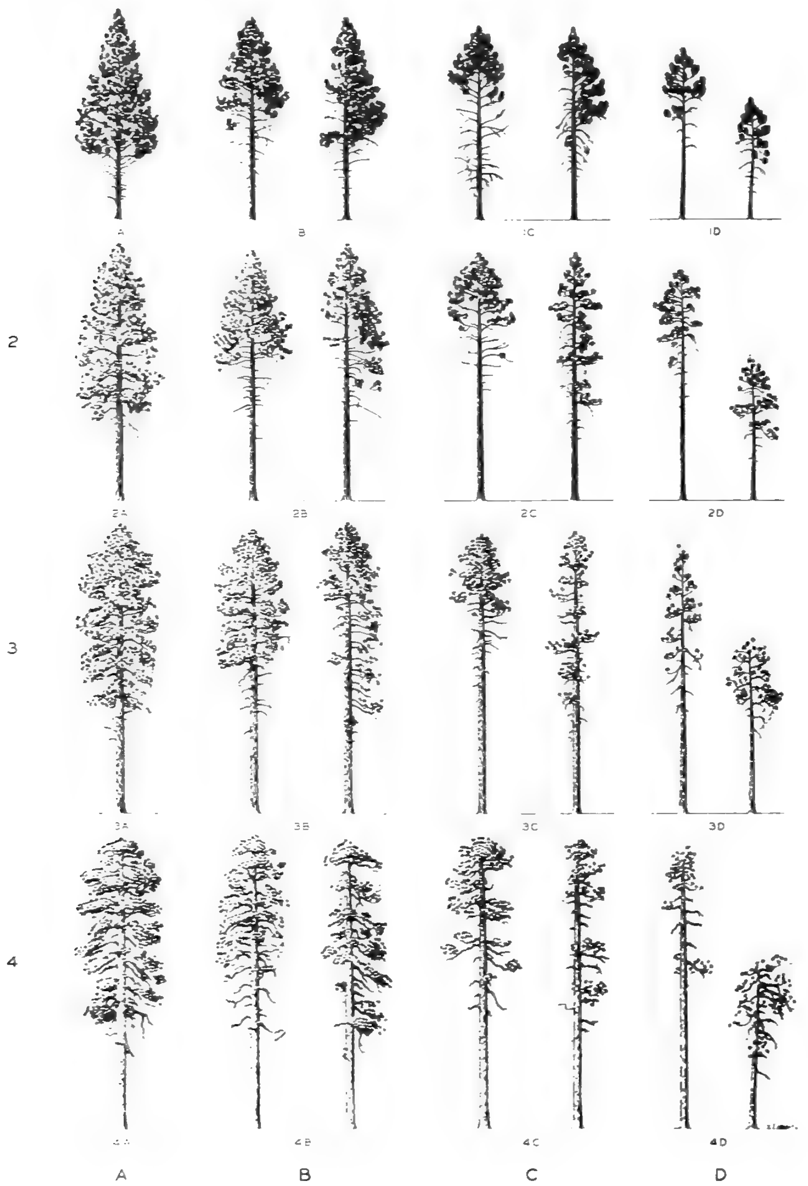

Figure 2.--The Keen ponderosa pine tree classification. Age increases from 1 to 4 and vigor decreases from A to D. (From Keen 1936.)

From 1928 to 1931 an impressive study was conducted in southern Oregon, near Ashland, in which 27,465 attacked trees were classified according to the Keen Tree Classes; and 22,428 unattacked trees were classified for comparison. The results showed a distinct improvement over the use of Dunning's vigor classes. Mortality ratios found ranged from 0.17 for trees with a high vigor classification to 2.50 for trees with a low vigor classification. The mortality ratio is the percentage of the loss in a given class divided by the percentage of that class in the original stand. Mortality ratios >1 denote susceptible classes. Therefore, the Keen Tree Classes provided, for the first time, a sharp and easily recognized difference among types of crown classes. However, there were too many trees in the susceptible classes, requiring the removal of too much of the stand. The development of the California System resolved this problem.

It is interesting to note that Dunning's classes were developed for ponderosa pine on the west slope of the Sierra Nevada, where the California System has been found unsuitable. Ecologically, east and west slope Sierra Nevada-Cascade have proved to be two quite different areas for ponderosa pine, and the insect complexes appear to be different and to operate differently in the two regions. This variation in site emphasizes the need to establish a sound ecological basis for risk studies.

An Insect Selection Cutting

Person shifted his base of operation from the west slope of the Sierra Nevada to northeastern California. And as Keen had done, Person started with Dunning's tree classes. In 1927 he established an experimental cutting on a 20-acre plot on the Modoc National Forest by using Dunning's classes and removing what were called "the most susceptible trees," although the classes were not identified. The purpose of the experiment was to determine for the first time if selection cutting could be used to remove susceptible trees and reduce subsequent loss. Shortly after Person established this experiment, K. A. Salman assumed responsibility for continuing the work. Salman seemed to benefit from Person's work on tree selection and was able to carry it forward to a risk system.

Increment cores were used to determine the year of tree death on both cut and uncut plots. From 1920 to 1927 ca. 28 percent of the stand had been killed at a fairly even annual rate. In the 4 years after the selection cutting, a 4 percent loss occurred in the untreated stand and a 1 percent loss in the treated stand. Salman (1932) concluded as Keen had that Dunning's classes did not discriminate risk clearly enough. Salient points of this study, particularly as they pertain to research and development processes are: it was the first experimental cutting in which a principle of insect selection was applied; the results were not strikingly successful; and scientists, particularly Salman, used the experience gained from this study to develop other and more profitable research.

CALIFORNIA PINE RISK-RATING SYSTEM

Development

Final formulation of the California System was made in 1936 by Salman, who

was convinced by his analysis of the study Person had established that Dunning's classes were unsuitable for rating risk. Salman also noted two limitations in the 16-class system developed at this time by Keen for use in southern Oregon. First, the 16 classes made it cumbersome as a working tool, and second, it would require the removal of too large a volume of timber for quick treatment of stands. If the forest manager was to reduce the chances of bark beetle losses, the cutting should be light enough to cover stands quickly.

Salman took advantage of the observations of workers making annual loss surveys in northeastern California in the early 1930's. They had reported that most trees killed could be characterized by various kinds and degrees of crown deterioration before attack. These observations were crystalized into a study by Salman in 1936, in which 973 infested and 2,026 unattacked trees were cut and carefully examined for various types of crown deterioration.

A three-class structure was preliminarily established, but Salman's field crew found that four classes were better for field application. Eventually the elements of high risk were described as follows (Salman 1937 and Salman and Bongberg 1942) (fig. 3):

> --thin or sparse foliage complement, short needles, and the dying of twigs and branches were characters of the trees that become infested and die--active or recent top-killing infestations, the localization of branch or twig injuries, and the thinning and shortening of foliage in portions of the crown also occurred in many of the trees that died--green trees which exhibited those characters were likely to die and were considered as high-risk trees. High-risk characters were absent in healthy appearing trees considered (lower) risk from insect attack under normal conditions--gradations were segregated into four degrees of risk for application in field tests.

Figure 3.--Four stylized trees, illustrating the four risk classes of the California Pine Risk-Rating System.

The next step was to test the classification more extensively and 18,056 ponderosa and Jeffrey pines were classified according to risk on the Modoc and Lassen National Forests. About 11 percent of the trees fell into Risk Classes III and IV, the high-risk classes (table 1); and about 84 percent of the attacked volume fell into the same two classes (table 2) (Salman and Bongberg 1942). These data show that bark beetles attacked and killed 23 trees or 30 fbm in high-risk categories (Risk III and IV) for every one, tree or fbm, killed in the low-risk categories (Risk I and II).

It is important to note, as pointed out by Keen and Salman (1942), that neither the Keen tree susceptibility classes nor the California System risk classes are, in themselves, a timber management system. They are, instead, silvical principles. The Keen Tree Class system associates 16 age and crown vigor classes with average annual susceptibility to attack. It should be noted that the four classes of the California System are somewhat similar to certain of the Keen Tree Classes. The California System associates four generalized crown types with the current probability of attack, i.e., risk of being killed. To become a timber management procedure, or tree-marking system, the objectives of the timber manager must be considered also, i.e., the amount to be cut, the purpose of logging, the speed at which the stand is to be logged, the type of residual stand required, and the method and time of regeneration. When the California System became a logging procedure, the term sanitation/salvage was applied to the operation. This term has since been used to describe any process of removing low-vigor, more susceptible trees.

Thus, by 1936 the California System was fairly well fixed and a period of testing and modification began. The development period was characterized by large studies which associated certain crown characteristics with subsequent tree mortality. In a sense it appears that Keen modified the existing vigor classification system of Dunning, while Salman developed his definitions from the results of several years' observation of thousands of trees, though he was aware of the other classifications. Keen's classification seems to have been the more logical approach; Salman's, though oriented toward practical application, seems to have rested on some intuition.

Table 1.--Distribution of green trees by risk ratings, by trees and volume

Risk rating	Number of trees	Percent of total number of trees	Volume b.m.	Percent of total volume b.m.
I	12,184	67.5	8,725,015	54.9
II	3,865	21.4	4,692,573	29.6
III	1,099	6.1	1,418,457	8.9
IV	908	5.0	1,047,644	6.6
Total	18,056	100.0	15,883,689	100.0

Source: Salman and Bongberg (1942).

Table 2.--Distribution of insect-killed trees by risk ratings, by trees and volume

Risk rating	Number of trees	Volume b.m.	Percent of total loss volume b.m.	Percent of loss in total volume b.m.	Mortality ratio[1] volume b.m.
I	16	11,142	4.1	0.13	1
II	27	31,130	11.4	0.66	5
III	43	44,579	16.4	3.14	24
IV	178	185,395	68.1	17.70	136
Total	264	272,246	100.0		
Average				1.71	

[1] Percentage of loss in Risk I considered as 1, or the unit of comparison.

Source: Salman and Bongberg (1942).

Testing

Salman reasoned that the removal of the high-risk trees from a stand would result in significant benefits and he proposed a logging experiment to test his theory.

The basic experiment to test and verify the California System was started in 1937 on the Blacks Mountain Experimental Forest, located in the north-central portion of the Lassen National Forest. All of the high-risk trees, i.e., Classes III and IV, were removed on a 322-acre compartment; added to the high-risk trees was a sufficient volume of lower-risk trees to ensure a cut of 2,500 fbm/acre. In the following 6 years additional compartments were treated each year until about 3,200 acres had been treated. The average volume removed was 15.7 percent of the merchantable stand. An annual 100-percent cruise of cut and uncut compartments provided data on loss by classes of trees.

Bongberg (1939) reported that the result of the first year's test was a very satisfactory 91 percent reduction in annual insect-caused timber loss. At the end of 10 years, Bongberg (1949) reported that the reduction in annual beetle-caused mortality ranged from 67 to 92 percent with an average of 82 percent for the 10-year period. The final results cover a 22-year period (table 3) (Wickman and Eaton 1962). If only insects are considered, this loss was reduced by 80 percent, i.e., 99.5 fbm/acre loss per year on the uncut blocks and 19.5 fbm/acre per year on the cut blocks. Annual mortality on treated and untreated plots varied considerably from plot to plot and from year to year. The mean annual loss ranged from 0 to 40.8 fbm/acre on the treated plots and from 9.4 to 249.0 fbm/ acre on the untreated plots. Part of this variation was attributed to year of cutting, since 6 years were required to establish the study; and part was undoubtedly attributable to the annual and spatial fluctuations in the beetle populations. The variation in the percent reduction from year to year ranged from a high of 97 percent in 1945 to a low of 38 percent in 1953 (fig. 4); neither year was an extreme of insect activity. Salman contended that risk rating was primarily a probability of current attack. If we consider that these probabilities lie in a confidence band, of say 90 percent, then we would expect by chance that twice in 20 years, deviations outside the confidence intervals would be observed. Al-

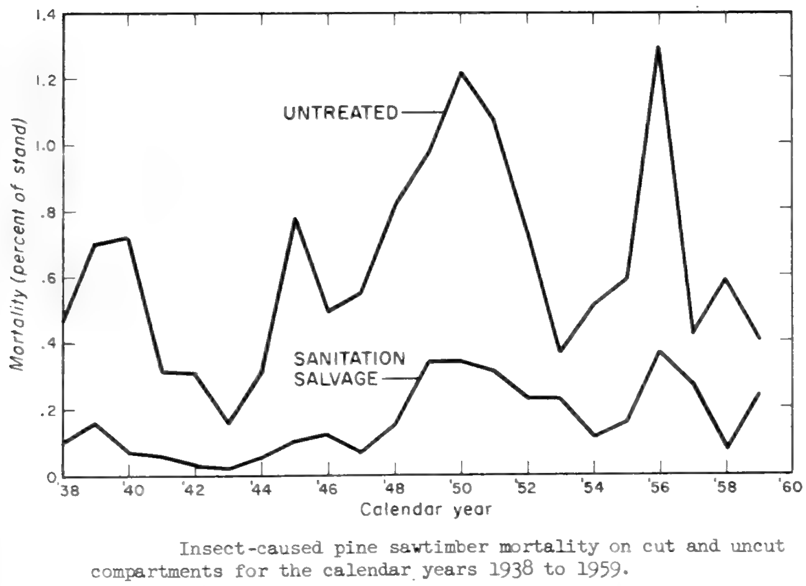

Figure 4.--Insect-caused pine sawtimber mortality on cut and uncut components for the calendar years 1938 to 1959. (From Wickman and Eaton 1962.)

though no estimates were made of confidence limits, we think this is the case. The cumulative insect-caused mortality (fig. 5) shows a steady and continued accrual of loss reduction.

A second study compared sanitation/salvage with several other types of Forest Service cutting methods (Eaton 1959). Results suggested that any system that removes a large volume of the total stand or much of the volume of trees with poor growth will reduce subsequent losses. In a sense it is a matter of getting to the tree before the beetle as well as improving growth conditions for the residual stand. Sanitation/salvage was the lightest of all cutting methods; therefore, it provided the quickest means of "sanitizing" an area as proposed by Salman.

The final step in establishing the sanitation/salvage procedures was a pilot test. In 1939, the McCloud River Lumber Company began logging under the guidance of Bongberg (1947). An area 10 miles north of Burney Falls, California, that had experienced continuing loss caused by WPB was marked using the California System. The cut of 563 fbm/acre was unusually light, but the cost of logging was only about 23 percent higher than a standard heavy cut. This additional cost was more than offset by the value of timber recovered that would have been lost to subsequent beetle attack. Insect-caused

Table 3.--Cumulative insect-caused mortality of pine sawtimber reserve per acre in successive numbers of years after cuttings, by treatment, 1938-59[1]

Year after cutting	Treatment and weighted mean reserve stand volume (board feet)			
	Sanitation/salvage (13,682 trees)		Untreated (16,358 trees)	
	Board feet	Percent stand	Board feet	Percent stand
1	14.7	0.11	89.3	0.55
2	22.8	0.17	172.0	1.05
3	26.8	0.20	251.2	1.54
4	38.2	0.28	325.0	1.99
5	53.6	0.39	418.1	2.56
6	68.5	0.50	514.3	3.15
7	77.8	0.57	626.4	3.83
8	108.2	0.79	749.3	4.59
9	134.0	0.99	878.0	5.37
10	170.0	1.24	1,016.2	6.22
11	204.5	1.49	1,154.7	7.07
12	258.5	1.89	1,301.5	7.97
13	272.7	1.99	1,420.5	8.69
14	297.7	2.18	1,540.7	9.43
15	323.9	2.37	1,640.6	10.04
16	357.7	2.61	1,741.9	10.66
17	384.8	2.81	1,844.2	11.29
18	403.8	2.95	1,950.6	11.94
19	422.0	3.08	2,059.5	12.60
20	473.3	3.46	2,135.4	13.07
21	494.7	3.62	2,215.3	13.56
22	514.9	3.76	2,281.3	13.96

[1] The first year after cutting is based on 3,200 treated acres and 9,250 untreated; the 22nd year is based on 81 treated acres and 407 untreated.

Source: Wickman and Eaton (1962).

loss in these stands was reduced by 85 percent over the next 6 years. Loss reduction was based on a projection of the loss experienced on the treated area for several years before logging. An unexpected and important benefit of sanitation/ salvage cutting materialized in 1944, when a rapid increase in WPB activity developed in the general geographic area. Losses in uncut stands were heavy and direct control operations were taken. Losses remained very low in the areas logged by sanitation/ salvage, however, and no direct control was necessary.

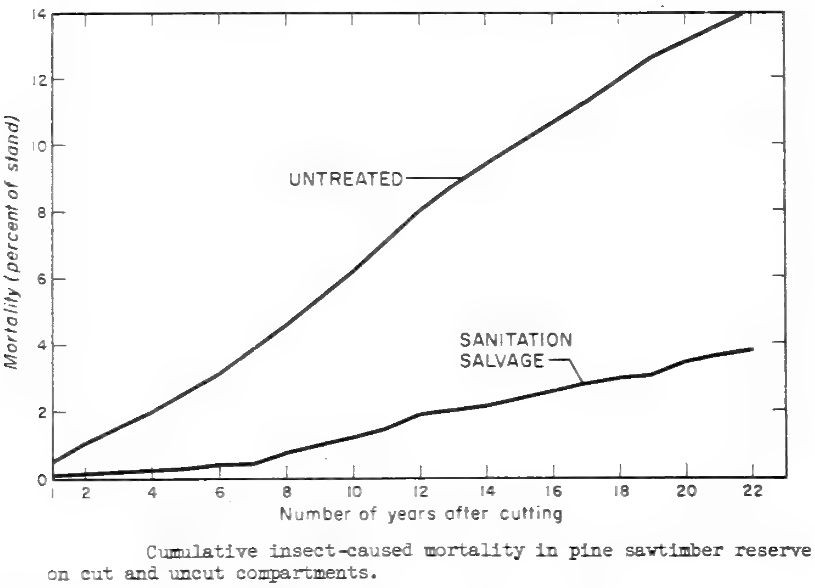

Figure 5.--Cumulative insect-caused mortality in pine sawtimber reserve on cut and uncut compartments. (From Wickman and Eaton 1962.)

Bongberg (1942) also applied sanitation/salvage to eastside Jeffrey pine and obtained results essentially the same as those obtained in ponderosa pine stands. This similarity showed the general suitability of the California System to stands of predominantly Jeffrey pine attacked by JPB.

These reports by Bongberg, Eaton, and Wickman and Eaton demonstrated conclusively the immediate, large, and lasting beneficial effects of applying cuttings to eastside ponderosa and Jeffrey pine based upon a risk-rating system. The next step was to determine the scope of its applicability as well as to establish it as a forest management tool.

Early Application

After the favorable results with sanitation/salvage on part of its holdings, the McCloud River Lumber Company adopted this method of management on the balance of its ponderosa pine stands.

In 1940, the U.S. Forest Service tested sanitation/salvage on 8,000 acres on the Dixie Valley Sale Area on the Plumas National Forest in a mixed ponderosa-Jeffrey pine type. The first year after treatment there was 100-percent reduction in loss of ponderosa and 82 percent of Jeffrey pine. In 1942, the Forest Service undertook another sanitation/salvage sale on the Lassen and Modoc National Forests and in subsequent years adopted sanitation/salvage as standard management procedure on all eastside pine stands that it managed.

In 1940, Collins Pine Company at Chester, California, tested sanitation/salvage with excellent results and adopted this method of treatment on its 80,000-acre tract. The company continues to use this method today in appropriate stands.

After the successful application of sanitation/salvage, many private timber operators in northeastern California adopted it as standard management procedure.

Expanded Use

Keen (1940) extended the use of the California System to southern Oregon with the establishment of logging studies by the Weyerhaeuser Timber Company near Klamath Falls. The studies used hybrids of Keen Classes and California Risk Classes because the early results of using risk classes were so promising in northeastern California. The logging removed slightly more than 10 percent of the volume. Early results (Keen 1942) showed that a hybrid-based cutting worked as well as one based solely on the risk classification. Continued evaluation of the study showed the hybrid to have the desirable long-lasting effects shown by the California System (Keen 1955). In the early 1940's, Orr (1945) applied the hybrid system to extensive areas in southern Oregon. In all, 200,000,000 fbm, comprising ca. 25 percent of the volume of the stands, were logged. Subsequent losses were judged to be markedly reduced. Sowder (1951) extended the use of California System still further north in eastside Cascade to the area of Bend, Oregon. These studies and applications greatly expanded the area of applicability to nearly all of ponderosa-Jeffrey pine stands east of the Sierra-Cascade crest.

Sanitation/salvage was applied operationally to a limited area in the coastal mountains of southern California in 1953 and 1954. Losses over the preceding years had become progressively heavier and the direct control efforts applied had not been fully satisfactory. Primarily a recreational area, cutting of green trees was not viewed with favor. However, increasing salvage of dead trees was looked upon with even less favor. Thus a sanitation/salvage operation was carried out

with favorable public support. Hall (1958) estimates that losses after sanitation/ salvage logging was conducted were less than 10 percent of the losses experienced before the operation. With this experience as a basis, some 80,000 acres of similar forest were logged by sanitation/ salvage operation between 1955 and 1957.

Although precise data were not recorded, Hall and Pierce (1965) estimated that losses on the recreational area were reduced by 60 percent for the first 6 years but then started to rise because of a rapid increase in the number of trees which became high risk. The area was logged again and the effect in subsequent years was favorable. In several other areas, a similar pattern developed and Hall applied direct control measures to suppress losses until sanitation/salvage could be applied. This procedure of combining sanitation/ salvage with direct control is often called maintenance control.

A long-term study was established in 1948 to determine the applicability of risk-rating to ponderosa pine in western Montana (Johnson 1972). A second objective of the study was to determine the threat of WPB in that area. In all, 11,946 pines were tagged, measured for size and volume, and risk-rated according to the California System criteria. In Montana a much greater percent of the volume fell into the middle classes and a much smaller volume in the extreme classes (table 4) than was found in California (Salman and Bongberg 1942). The combined percent in risk III and IV--the trees usually cut in a sanitation/ salvage operation--is somewhat similar, with 11 percent in California and 20 percent in Montana.

Table 4.--A comparison of stand and loss volume, by percent, in the four risk classes in California[1] and Montana[2]

Risk	California Stand	California Loss	Montana Stand	Montana Loss
I	68	4	8	0
II	21	12	72	24
III	6	16	17	42
IV	5	68	3	34

[1] Data from Salman and Bongberg (1942).
[2] Data from Johnson (1972).

Bark beetle activity in ponderosa pine in Montana during the period of the study was lower than that experienced in northeastern California during the period of development of the California System. Nevertheless, the apportionment of loss in the various risk classes was quite similar. The results, therefore, suggest that the risk principles are applicable to low endemic conditions as well as to outbreak conditions. They further indicate that the percentage of high-risk trees in the study area is sufficient to support an outbreak of bark beetles when other factors become favorable for an increase in the beetle population. Even before the California System had been tested in Montana by Johnson's experiment, many land managers in the intermountain region, such as J. Neils, Anaconda Copper, Potlach, as well as the U.S. Forest Service and Montana State Forestry Division, were applying it to stands which were considered to be of the same type as the stands in California and Oregon (Johnson 1951).

Refinement: Penalty System

A refinement of the California System is the penalty system in which penalty points are assigned to crown and stem characteristics of a tree. The penalty system was devised primarily as a way to train inexperienced tree-markers in using the risk system. Usually after a day or two with a penalty card, the marker felt confident in continuing without the aid of a card.

The first penalty system, formulated in 1941 (Keen 1954), was based upon the association of crown or stem characteristic with risk classes and subsequent tree mortality. Values, called penalties, were assigned to these associated characteristics. Thus, the stronger the association of the characteristic with risk and tree mortality, the larger was the value and the greater the penalty. In practice, a penalty card was scored according to a quick visual assessment of the crown and trunk. Keen's original system has been modified several times, the last by Hall (1951) (table 5).

Derivative: Stand Hazard

No sooner had the California System been preliminarily formulated than entomologists turned their attention in 1937 to developing a system for rating stand hazard. The 1936 field season was spent in developing indices for classifying some 2 million acres of ponderosa-Jeffrey pine type in northeastern California (Salman 1938). As a result of this study two separate but related stand characteristics were used for hazard classification (Miller et. al. 1941) (Johnson 1949): (1) the past 10 years' cumulative volume of beetle-caused mortality, (2) the current volume of high-risk trees in the stand. The current green volume of the stand was determined and two percentages were calculated by dividing each of the above volumes by the green stand volume. The two

Table 5.--A penalty card with values for crown characteristics and four risk classes

PENALTY SYSTEM FOR RATING HIGH-RISK TREES
Eastside Ponderosa and Jeffrey Pine

	Penalty
A. NEEDLE CONDITION	
1. Needle complement	
a. Needle complement normal	0
b. Less than normal needle complement through crown. No contrast between upper and lower crown	2
c. Thin complement in upper crown, normal in lower crown. Contrast evident in upper and lower crown	5
2. Needle length	
a. Needle length normal	0
b. Needles shorter than normal throughout crown. No contrast between upper and lower crown	2
c. Needles short in top, normal below. Marked contrast	5
3. Needle color	
a. Normal	0
b. Off color	2
c. Fading	8
B. TWIG AND BRANCH CONDITIONS	
1. No twigs or branches dead	0
2. A few scattered dead or dying twigs or branches in crown	1
3. Many scattered dead or dying twigs or branches in crown	2
4. Dead or dying twigs or branches in crown forming a definite weak spot in crown, notably in top 1/3 of crown	3
5. Dead or dying twigs on branches in crown forming more than one weak spot or hole, notably in top 1/3 of crown	5
C. TOP CROWN CONDITIONS	
1. No top killing	0
2. Old top kill with no progressive weakness or killing in green crown below	5
3. Current top killing	8
4. Broken top--recent, less than 1/3	5
5. Broken top--recent, more than 1/3	8
6. Broken top--old, no progressive weakness	2
D. OTHER FACTORS	
1. Lightning strikes--recently struck, no healing evident	8
--healed strike	2
3. *Dendroctonus valens* attacks in base--current, successful	6
--old, pitched out	2

The following factors have local significance and will differ by area. We have little information on their importance, and the marker should weight these in terms of local observation and experience.

3. Mistletoe
4. Needle scale (various spp.)
5. Needle blight (*Elytroderma deformans*)
6. Rust (*Cronartium* spp.)

Risk class	Penalty score
I	0
II	1 to 4 inc.
III	5 to 7 inc.
IV	8 and higher

Source: Hall (1951)

percentages were added and five stand (or beetle) hazard classes were established; values less than 4 were considered very low hazard and 27 or more considered very high hazard. A map showed areas with various degrees of hazard (fig. 6). With this information the land manager could then direct his logging to the most hazardous stands first in order to reduce losses until a normal high volume logging operation could be installed.

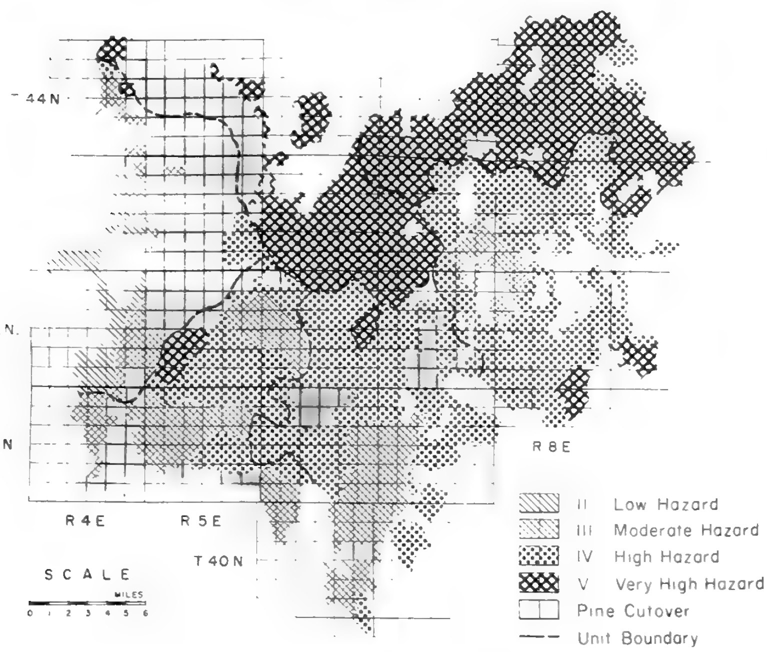

Figure 6.--Relative hazard is illustrated in this map of eastern Lassen County, California. (From Miller et al. 1941.)

Contingent Research

After the California System was established, several studies analyzed, explained, qualified, or elaborated the principles behind risk; six of these are worthy of brief review.

Changes in Risk

The question was logically asked about the permanence in the risk class of a tree, i.e. does the risk of a tree tend to increase gradually (or quickly), does it remain fairly constant, or does it even decrease?

Eaton (1941) initiated a photographic study to answer these questions. Forty-eight trees representing the four risk classes were selected for periodic photography. Furniss (1954) reports the following results after 13 years:

Accidentally cut	5
Killed and showed increase in risk	11
Still alive	32

The 32 trees still alive showed as follows:

An increase in risk	2
No change in risk (fig. 7A)	3
A decrease in risk (fig. 7B)	27

Figure 7A.--Tree shows no change in risk from 1942 (left) to 1953 (right). (From Furniss 1954.)

Figure 7B.--Tree shows decrease in risk from 1942 (left) to 1953 (right). (From Furniss 1954.)

Others found much the same phenomenon after reclassifying large numbers of trees. Records were not kept on specific trees, but the average risk structure of the stand improved over a period of several years.

These studies were conducted over the same climatic cycle in which there was a general improvement in precipitation, which is usually assumed to be a factor regulating risk. Thus, risk can be a reversible process; but because many trees did not show improvement, the factors and processes expressed by risk may not be simple.

In another locality, however, Furniss and Hallin (1955) found a slow change to high-risk trees. They recorded one high-risk tree per acre in an area 16 years after all such trees had been removed.

California Flathead Borer

Incipient attacks by the borer *(Melanophila californica* VD.) were suspected as one of the more important agents which determined the condition making a tree high risk. Substantial effort was made to confirm these suspicions. Salman (1940) concluded from a 4-year study that incipient infestations of the borer tended to occur more frequently in trees that were killed, and that the incidence of incipients was much greater in the higher-risk classes. However, incipient attacks could be found in low-risk trees. The borer appeared to be part of the whole risk phenomenon, but other factors were involved as well.

Crown Analysis

Since risk is based almost entirely on crown characteristics, Wygant (1942) studied in detail these crown and stem components: (1) needle fascicles per twig, (2) needle length, (3) needle diameter, (4) annual twig growth in length and (5) in diameter, (6) annual radial growth in different parts of the stem. For all components he found that the values for low-risk trees were much greater, usually significantly so, than for high-risk trees (table 6). The one measure that did not change was needle retention. Trees in both risk I and IV retained needles for 5 to 6 years. Other studies have shown that the period of needle retention is largely controlled by local environmental conditions.

Accuracy of Risk-Rating

Though much effort was made to make risk-rating objective and to define classes as distinctly as possible, the four classes overlap and there is still considerable subjectivity in assigning trees to classes. Thus the accuracy of comparing risk-rating among observers or two evaluations by the same observer come into question. Among the many studies of this problem, the one by Eaton (1942) illustrates the general results. He found the agreement among expert risk-raters was about 80 percent, i.e. experts disagree on the risk class of about 20 percent of the trees (fig. 8). He concluded that the percent of agreement improves with experience, and that there was close agreement among experienced classifiers using all three tree classification systems. But, inexperienced raters used the risk system more accurately than the Keen or Dunning classifications.

In commenting on Eaton's results, Keen[2] reports that trained survey crews were about as accurate as trained forest entomologists in using Keen Tree Classes, and both groups were considerably better than untrained rangers.

[2] Personal communication to J. M. Miller, April 9, 1942, on file at Pacific Southwest Forest and Range Experiment Station, P. O. Box 245, Berkeley, California, 94701.

Table 6.--Average growth characteristics of 16 Risk I and of 17 Risk IV ponderosa pines

	Top crown		Mid crown[1]		Lower crown[2]	
	Risk I	Risk IV	Risk I	Risk IV	Risk I	Risk IV
Number of needle fascicles per twig	197.4	119.1	188.1	108.8	173.9	
Needle length in inches	6.22	4.91	6.47	4.96	6.56	
Needle diameter in mm	1.87	1.80	1.86	1.76	1.80	
Annual twig growth in inches, 1917-1940	.80	.58	.72	.57	.70	
Twig diameter in cm	1.52	1.23	1.38	1.10	1.32	
Annual radial stem growth inches, 1912-1941	.0128	.0105	.0211	.0112	.0144	.0126

[1] For radial stem growth this column should be headed "mid bole."
[2] For radial stem growth this column should be headed "stump."

Source: Wygant (1942).

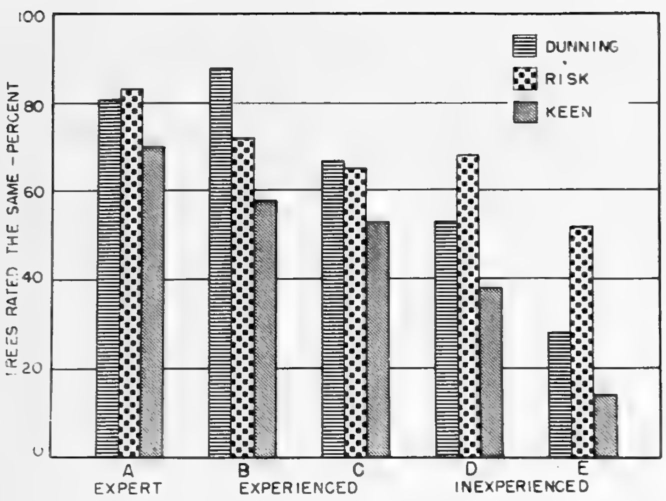

Figure 8.--Frequency of agreement in two sets of tree class ratings made by men of different experience levels, based on observations on 100 trees. (From Eaton 1942.)

These two studies, along with many others of the same type, illustrate the very important point that there is still some imprecision in the risk system for an individual tree. However, for a stand, the effects average out, and cutting the high-risk trees reduces subsequent losses.

It is important to keep this imprecision in mind when studies of individual trees do not produce clear results. There is an inaccuracy in rating the tree, a further uncertainty in risk itself, a compounding phenomenon of changing risk, and changing environmental conditions which might override all these factors.

Brood Production

Just how the risk class of a tree functions in the dynamics of the beetle population is a basic question. Curiously enough, it has had surprisingly little attention, probably because the system works so well that scientists felt it was more profitable to expand and refine the use of risk rather than attempt to explain its mode of operation. It is generally hypothesized that high-risk trees are most easily overcome by the beetles. But how does this influence the beetle population?

Hall (1942) recorded brood production from trees of the four risk classes. The results, even though based on only four to seven trees per risk class, are striking (table 7). Emergence per square foot of bark surface was 18, 24, 44, and 115 beetles for Risk Classes I, II, III, and IV, respectively. The ratio of attacking to emerging beetles was not measured, but the results suggest that high risk trees can provide a source of population maintenance and may provide a real impetus to population increase.

Table 7.--Emergence of adult western pine beetle from bark of infested trees of the four risk classes

Risk class	Trees sampled	Ft^2 of bark	Total beetles emerging	Emergence per ft^2
I (low)	4	29	510	18
II (medium)	4	33	795	24
III (high)	7	56	2488	44
IV (very high)	7	57	6543	115

Source: Hall (1942).

If we assume an average of 12 attacking pairs per square foot and inflight mortality of 75 percent, only the high-risk trees would produce sufficient brood to support an increasing population. Such a situation might exist under endemic conditions but might not prevail under epidemic conditions, where the enormous beetle population and some overall change in host condition could override much of the influence of risk.

Resin Flow

For as long as forest entomologists have been observing bark beetles in conifers, they have associated attack failure with copious resin flow. Little experimentation was attempted, however, until Callaham (1955) investigated resin flow from trees rated for risk and for Keen tree classes by using permanent plot trees on the Blacks Mountain compartments. Additionally, he had both Keen and Bongberg rate the permanent plot trees again. Not surprisingly, their agreement exceeded 80 percent for the risk I and III trees but dropped to less than 60 percent for the risk II and IV trees. Their lack of agreement was particularly pronounced in the very high-risk class, i.e. IV, with one rating 25 trees and the other only 5 in that class. Callaham's hypothesis was that low-risk trees would have greater flow of resin and, therefore, would be less likely attacked and killed. To test this hypothesis, resin flow from a standard wound was measured. Although there was less flow of resin from high-risk trees, mean values for the total flow of resin were not significantly different among risk classes. There were significant differences in the duration of flow however. Resin flow from the low-risk trees, i.e. I and II, continued much longer than from high risk trees, i.e. III and IV. There was appreciable flow of resin from low-risk trees even after the fourth day after wounding, while resin flow from very high-risk trees had nearly stopped by then.

Callaham (1955) hypothesized that the shorter duration of resin flow from high-risk trees permitted successful attack by the beetles while the continued flow from low-risk trees prevented successful attack. Because the study was conducted toward the end of the period in which Eaton (1941) and Furniss (1954) studied change in risk, the lack of sharp differences might have been caused by some basic improvement of tree condition prior to external evidence of change of risk.

SYSTEMS FOR TRUE FIRS

Risk-rating systems derived from the California System have been developed for individual, mature red firs (*Abies magnifica* A. Murr.) and white firs (*A. concolor* Gord. and Glend.) (Ferrell 1980). These systems, as yet untested, predict the probability of tree death within 5 years based mainly on the same crown characteristics used by the California System. The fir systems were developed by using computer-based analytical techniques for extensive cutover and virgin, old-growth stands of these firs in northern California. For routine field use, the systems have been formulated on an award/penalty basis in which trees are awarded points based on some characteristics, and penalized points based on others.

To expedite development of preliminary systems, characteristics of recently dead and live firs, obtained during initial survey of 47 20-acre plots, were computer-screened and major predictors of risk were selected from the resulting "decision tree" output. Risk equations, predicting 1-year probabilities of tree death, were developed by regressions based on the logistics model, then tested for goodness-of-fit to the observed distribution of mortality in the data base. One-year probabilities were extrapolated to 5-year probabilities by using a variant of the standard compound interest formula. For field use, the equations were translated into Award-Penalty Point Systems based on the signs of the predictors' regression coefficients. Annual surveys of tree mortality and decline are continuing in order to refine the present systems, producing final systems capable of predicting risk over longer time periods.

SUMMARY AND CONCLUSIONS

The California Pine Risk Rating System is basically a silvical principle which rates the current probability of attack by insects, primarily western and Jeffrey pine beetles for eastside ponderosa and Jeffrey pine. The System is based on the classification of individual trees by easily and quickly recognized crown characteristics. When the system is utilized as a forest management practice, it is called sanitation/salvage logging. It has been found to be highly effective in reducing losses by bark beetles on applicable forest sites. The removal of as little as 10 to 15 percent of the stand volume, as high-risk trees, reduces subsequent losses by as much as 80 percent for more than 20 years.

The California System evolved during the period 1925 to 1940 in California and southern Oregon. It was the first risk-rating system of its kind to be developed and applied. The experiences of research on tree selection and classification, and the analysis of large-scale bark beetle surveys and direct control programs formed the background of information and attitudes for the research and development of the California System. This endeavor commanded the whole or partial attention of some of the most competent forest entomologists in the West. Contributions were made by many whose names do not appear on the cited reports and publications, through their participation in meetings, consultations, and correspondence. Those early scientists accomplished an amazing amount of high-caliber work without many of the tools and amenities of today's research. They also seemed to apply a fortunate balance of logic and intuition along with careful and extensive field observations. This was also the developmental period for the forest entomologists who did many of the basic studies on forest insect pests in the West.

The critical study which resulted in the formulation of the System was designed and conducted by K. A. Salman, who was guided by results of careful research, collaboration, and testing of many scientists and forest managers. His study in 1936 resulted in the definition of four risk classes, based primarily on kinds and degrees of crown deterioration. This formative research was followed by large-scale logging studies starting in 1937 on the Blacks Mountain Experimental Forest on the Lassen National Forest. These studies were highly successful in proving the immediate, large, and lasting favorable benefits of sanitation/salvage logging. The first use of the System by private forestry was designed by J. W. Bongberg in 1939 for the McCloud River Lumber Company in Shasta County, California. This operation demonstrated both its effectiveness and ease of application. The California System meets most of the requirements of a good forest practice; it is easy to apply, is economical, and has large and lasting favorable benefits with a minimum of adverse environmental effects. It was adopted as a standard management practice by the U.S. Forest Service in Region 5 and by many timberland owners in California and Oregon.

Three important modifications or derivatives of the System are a stand hazard classification system, a penalty scoring procedure, and an award/penalty system for risk rating true firs. The stand hazard classification uses risk-rating values of a stand and the recent past experience of insect-caused losses to rate the relative need of areas for pest management attention, either survey or control. That is, hazard rating is a guide to the resource manager to target or intensify surveillance or to direct his sanitation/salvage operation. The penalty scoring procedure was designed to train timber markers and to increase the objectivity of risk rating by assigning numerical penalties to easily recognized tree characteristics. The sum of the penalties determines the risk class of a tree. The award/penalty system for risk rating individual true firs uses the principles and procedures developed by the California System and can be considered a derivative of it.

In 1962, efforts were made to define more clearly the risk classes through the use of several types of recently developed statistical procedures. The results of the analysis did not improve the definition or identity of the risk classes. However, recently developed analytical procedures using computers were effectively used in the work on true fir.

Subsequent research has attempted to explain the System and its mode of operation in the dynamics of the tree and the beetle. One study showed the expression of crown deterioration was largely a function of size, growth, and position of needles and twigs. Another study showed that the duration of xylem resin flow was shorter for high-risk trees than for low-risk trees. Also, high-risk trees produced the largest number of beetles. The risk classification of a tree can change over long periods; some trees showed improvement, others showed decline. Another study showed the accuracy and repeatability in rating the risk class of trees is increased by experience.

Although risk rating is based on individual trees, it appears to function most effectively on an area basis. This is probably caused by the compensating action of such factors as imprecision of definition, inaccuracy in rating, changes in risk, overall shifts in environmental conditions, and the spatial and temporal fluctuations in beetle populations.

The System has been widely applied via sanitation/salvage logging on private and public forests of the eastside pine type of northeastern California and southern and eastern Oregon. In many areas the System has been effectively hybridized with the Keen Tree Classes. The extent of its use is difficult to determine, but there may be 3 to 5 million acres of applicable forests which have been processed to some degree by sanitation/salvage logging. Also, it has been found to be generally applicable to ponderosa and Jeffrey pine stands that are under long-term stress; such stands occur in southern California and intermountain regions of Montana and Idaho. The System may be more widely used than direct evidence can show because the terms risk and sanitation/salvage or derivatives of them are now standard terminology in forest practice; thus, the principles of the California System may be applied without the conscious effort to identify the System.

The California Risk Rating System is one of the more notable developments in forest insect control because of its intrinsic value. It has also been of inestimable extrinsic value in demonstrating the possibilities of utilizing insect/host relationships in pest control for a wide variety of insects.

It would seem advisable to close with an air of optimism and hope for future risk-rating systems. But we have chosen to close with a precautionary note as expressed by Craighead et al., (1931) as they concluded about bark beetle control in general.

> However, at least one outstanding conclusion applies to the entire matter, (of bark beetle control) and may be stated as follows: Each species of bark beetle presents its own special problem and must be dealt with differently from other species as to control methods and strategy, and even the same species may present problems which differ in different regions. The management of control operations must therefore vary according to local conditions within the area being protected.

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LITERATURE CITED

Bongberg, J. W. 1939. Loss prevention studies Blacks Mountain Experimental Forest, Season 1938. 11 p.*

Bongberg, J. W. 1942. Descriptions and illustrations of risk ratings for ponderosa and Jeffrey pine in eastside areas of California. 7 p.*

Bongberg, J. W. 1947. Experimental cutting for beetle control at McCloud River Lumber Company. The Timberman 48(7):128-130.

Bongberg, J. W. 1949. Results of ten years of bark beetle control by logging high risk trees, Blacks Mountain Experimental Forest, Lassen County, Calif. 18 p.*

Callaham, R. Z. 1955. Oleoresin production in the resistance of ponderosa pine to bark beetles. 84 p.*

Craighead, F. C. 1925. The Dendroctonus problem. J. For. 23(4):340-354.

Craighead, F. C., J. M. Miller, J. C. Evenden, and F. P. Keen. 1931. Control work against bark beetles in western forests and an appraisal of its results. J. For. 29-1001-1018.

Dunning, D. 1928. A tree classification system for the selection forests of the Sierra Nevada. J. Agric. Res. 36:757-771.

Eaton, C. B. 1941. A photographic study of risk trees. 5 p.*

Eaton, C. B. 1942. Variation in the application of tree classification systems to ponderosa pine. 13 p.*

Eaton, C. B. 1959. Insect-caused mortality in relation to methods of cutting in ponderosa pine on Blacks Mountain Experimental Forest. 33 p. U.S. Dep. Agric. For. Serv., Tech. Pap. PSW-243. Pacific Southwest For. Range Exp. Stn., Berkeley, Calif.

Ferrell, G. T. 1980. Risk-rating systems for mature red fir and white fir in northern California. 29 p. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. PSW-39. Pacific Southwest For. Range Exp. Stn., Berkeley, Calif.,

Furniss, M. M. 1954. A photographic study of the change of insect risk in ponderosa pine. 11 p.*

Furniss, M. M., and W. E. Hallin. 1955. Development of high-risk trees in ponderosa pine and Jeffrey pine stands following sanitation/salvage cutting. 2 p. U.S. Dep. Agric. For. Serv., For. Res. Note 94. Calif. For. Range Exp. Stn., Berkeley.

Hall, R. C. 1942. High risk trees are high producers of western pine beetles. 2 p.*

Hall, R. C. 1951. Penalty system for rating high-risk trees: eastside ponderosa and Jeffrey pine. 1 p.*

Hall, R. C. 1958. Sanitation/salvage controls bark beetles in southern California recreation areas. J. For. 56(1):9-11.

Hall, R. C., and J. R. Pierce. 1965. Sanitation treatment for insect control. 21 p.*

Johnson, P. C. 1949. Determining the bark beetle hazards of pine stands in northeastern California. J. For. 47(4):277-284.

Johnson, P. C. 1951. Application of risk ratings for western pine beetle control in the Inland Empire. Northwest Science 25:32-37.

Johnson, P. C. 1972. Bark beetle risk in mature ponderosa pine forests in western Montana. 32 p. U.S. Dep. Agric. For. Serv., Res. Pap. INT-119. Intermountain For. Range Exp. Stn., Ogden, Utah.

Keen, F. P. 1936. Relative susceptibility of ponderosa pines to bark beetle attack. J. For. 34(10):919-927.

Keen, F. P. 1940. Pine beetle control logging experiment on the Weyerhaeuser Timber Company, Bly District, Oregon. 20 p.*

Keen, F. P. 1942. Second year's results on the pine beetle control logging experiment of the Weyerhaeuser Timber Company, Rail Glade area, Bly District, Oregon. 12 p.*

Keen, F. P. 1943. Ponderosa pine tree classes redefined. J. For. 41(4): 249-253.

Keen, F. P. 1954. Ponderosa pine tree characteristics indicative of high risk to pine beetle attack: a progress report on studies conducted in eastern Oregon, 1938-1952. 49 p.*

Keen, F. P. 1955. Thirteen years' results of a test of pine beetle control logging by the Weyerhaeuser Timber Company, Swede Cabin Area--Bly District, Oregon, 1941-1953. 11 p.*

Keen, F. P., and K. A. Salman. 1942. Progress in pine beetle control through tree selection. J. For. 40(11):854-858.

Miller, J. M. 1926a. The western pine beetle control program. J. For. 24(8):897-914.

Miller, J. M. 1926b. Report of western pine beetle studies and experiments on the Cascadel Unit, North Fork, California. 9 p.*

Miller, J. M. 1933. A record of winter kill of western pine beetle in California. J. For. 443-446.

Miller, J. M., K. A. Salman, and P. C. Johnson. 1941. Bark beetle hazards in pine stands of northeastern California: Part II, Methods and basic data. 277 p.*

Miller, J. M., and F. P. Keen. 1960. Biology and control of the western pine beetle. 381 p. U.S. Dep. Agric. For. Serv., Misc. Publ. 800.

Orr, T. J., Jr. 1945. Selective marking in ponderosa pine on a Klamath Falls tree farm. J. For. 43:738-741.

Person, H. L. 1926. Report on studies on tree selection by the western pine beetle. 15 p.*

Person, H. L. 1928. Tree selection by the western pine beetle. J. For. 26(5):564-578.

Person, H. L. 1931. Theory in explanation of the selection of certain trees by the western pine beetle. J. For. 29(5):696-699.

Salman, K. A. 1932. Results of an experimental cutting in the Timber Mountain sample plot, Modoc National Forest. Prog. Rpt. Season 1931. 7 p.*

Salman, K. A. 1937. Preliminary results: Test markings of tree susceptibility. 5 p.*

Salman, K. A. 1938. Insect hazards to the pine resources of northeastern California. 8 p.*

Salman, K. A. 1940. A preliminary study of the diameter growth of ponderosa pine and of some of its relations with risk and incipient infestations of the flathead borer, (*Melanophila californica* VD.). 33 p.*

Salman, K. A., and J. W. Bongberg. 1942. Logging high-risk trees to control insects in the pine stands of northeastern California. J. For. 40(7): 533-539.

Sowder, J. E. 1951. A sanitation/salvage cutting in ponderosa pine, Pringle Falls Experimental Forest. 24 p. U.S. Dep. Agric. For. Serv., Res. Pap. PNW-2. Pacific Northwest. For. Range Exp. Stn.

Struble, G. R. 1942. Cascadel tree selection plot: a study of tree selection by the western pine beetle, final report. 22 p.*

Wickman, B. E., and C. B. Eaton. 1962. The effects of sanitation/salvage cutting on insect-caused mortality at Blacks Mountain Experimental Forest, 1938-1959. 39 p. U.S. Dep. Agric. For. Serv., Tech. Pap. 66. Pacific Southwest For. Range Exp. Stn., Berkeley, Calif.

Wygant, N. D. 1942. Studies of physical characteristics of high and low risk ponderosa pine, Black's Mountain Experimental Forest, Season of 1941. 19 p.*

*Unpublished report on file at Pacific Southwest Forest and Range Experiment Station, P. O. Box 245, Berkeley, California 94701.

AN EVALUATION OF THE HAZARD-RATING SYSTEM FOR BALSAM WOOLLY APHID DAMAGE IN NEWFOUNDLAND

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Abstract.--The balsam woolly aphid, *Adelges piceae* (Ratz.), a serious introduced insect pest of balsam fir, *Abies balsamea* (L.) Mill., is a persistent problem of all susceptible forests in Newfoundland. A damage hazard-rating system that permits forest managers to identify stands where there is a significant risk of severe damage has been used in long-term plans to identify priority sites where silvicultural control procedures should be applied. However, low aphid populations and a widespread severe infestation of spruce budworm, *Choristoneura fumiferana* (Clem.), have obscured the need for application of aphid hazard, especially in short-term, operational management plans. This paper discusses the combined effects of these two insect pests on the forest. The need for a hazard-rating system that incorporates the risk of injury from several insect pests is indicated.

INTRODUCTION

The balsam woolly aphid, *Adelges piceae* Ratzburg, a minute, sucking insect, is a pest of true firs (*Abies* spp.). This insect is originally from Europe, but it has been a resident in parts of eastern Canada and the Northeastern United States for the past 80 to 90 years. More recently, it has become a pest in Oregon, Washington, British Columbia, and North Carolina. Damage by this pest is greater in eastern North America than elsewhere because the host species--balsam fir, *A. balsamea* (L.) Mill. and Fraser fir, *A. fraseri* (Pursh) Poir.--are highly sensitive to the salivary injections of the insect (Balch 1952). Natural factors controlling the pest are inadequate (Clarke et al. 1971) and applied chemical and biological control techniques have proven unsuccessful or too costly to apply on a large scale (Hopewell and Bryant 1969). Infestations reduce growth, cause die-back, and usually result in the death of trees after several years of attack (Schooley and Bryant 1978).

The balsam woolly aphid was discovered in Newfoundland in 1949. About 800 km^2 of forested area were infested at that time. However, the infested area rapidly increased to about 16,000 km^2 in 1970. This area includes virtually all the susceptible balsam fir forest on the Island (Schooley 1968). A pest problem of this size attracted considerable attention, and a great deal of research was conducted between 1950 and the present. Aphid sampling and survey procedures were developed, the life history and biology of the aphid were examined, control methods were tested, and assessments were made of the impact of aphid damage on trees and stands (Schooley and Bryant 1978).

Perhaps the most significant outcome of the balsam woolly aphid research in Newfoundland was the development of a damage hazard-rating system (Page 1975). The system enables forest managers to identify sites and balsam fir stands where there exists a significant risk of severe aphid damage. This paper outlines and evaluates the hazard-rating system with particular reference to a widespread outbreak of spruce budworm (*Choristoneura fumiferana* [Clem.]).

THE DAMAGE HAZARD-RATING SYSTEM

In the early 1970's, aphid damage appraisal surveys were conducted throughout the Island. Data on the distribution and severity of damage were examined in relation to a multitude of stand, site and topographic variables (Page 1975). Elevation, soil-moisture regime, stand age, percentage fir composition, and total fir basal area were identified as significant variables related to damage. The elevation of an area, relative to the elevation of surrounding hills within 5 km, presumably acts as a measure of the degree of protection from weather and climatic factors that adversely affect aphid populations. Soil-moisture regime indicates natural moisture stress: severe aphid damage and mortality more frequently occur on the drier, freely drained sites than on wetter, poorly drained sites. Breast-height-age indicates the height and diameter of trees: frequently the larger, older trees, those more than 45 years old, are the ones most severely affected by the aphid. Percentage balsam fir by basal area and total basal area of balsam fir indicate stand composition and productivity: aphid damage is characteristically more severe in the most productive stands.

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Page used the above information to devise a system for classifying sites and stands in terms of their hazard of aphid damage. He provided equations that identified the probable incidence of severe damage in terms of three elevation classes: (I) lands below maximum elevation of severe damage, (II) lands above the preceding class but below the maximum elevation of any damage, and (III) lands above the maximum elevation of all damage. Lands in elevation classes I and II were further subdivided by three breast-height-age classes (< 25, 25 to 45, > 45 years) as either dry-fresh or moist-wet, as having a basal area of > or < 40 percent balsam fir, and as having a total balsam fir basal area of < 25 or > 25 m^2/ha. One of seven severe damage-hazard ratings was then assigned to each cell in the above classification framework on the basis of the expected percentage of balsam fir basal area to be severely damaged or killed by the aphid. The ratings used were as follows:

Severe damage-hazard rating		Expected percentage of fir severely damaged or killed
Nil		0
Very low	Vl	1-5
Low	L	6-11
Low-moderate	Lm	12-17
Moderate	M	18-23
Moderate-high	Mh	24-20
High	H	30+

The severe damage-hazard ratings for sites and stands in areas of elevation class (I) are given in table 1. Ratings for sites and stands in class (II) are all two hazard levels below those in table 1, and in most situations the hazard of severe damage is low or absent. Aphid damage does not occur in elevation class (III) areas.

Table 1.--Severe damage-hazard rating for sites and stands in elevation class I (below usual maximum elevation of severe damage) (Page 1975, table 6)

Moisture regime	Percentage fir by basal area	Total fir basal area (m^2/ha)	Breast-height age <25	25-45	>45
Dry-fresh	<40	Any value	L	Lm	Mh
	>40	<25	M	Mh	H
	>40	>25	M	H	H
Moist-wet	<40	Any value	Vl	Vl	Lm
	>40	<25	Vl	M	M
	>40	>25	L	Mh	Mh

To apply the system, the elevation classes are first defined using large-scale topographic maps and the equations provided by Page (1975). The remaining information required is available from forest inventory and capability maps, supplemented where necessary by additional ground data and/or photo interpretation. The system is equally useful and applicable to an individual stand, a watershed, or a management unit.

Approximately 40 percent of Newfoundland, excluding the Northern Peninsula, or about 4.5 million ha, falls into elevation classes (I) and (II). It is estimated that about 1.6 million ha has forest dominated by balsam fir and has a potential for severe aphid damage. Most of the accessible and productive balsam fir forests are included within this area. In the early 1970's it was estimated that the aphid was causing a volume loss of about 50,000 m^3/ year (Jarvis 1972). This was equivalent to about 4 percent of the total annual allowable cut of balsam fir being produced under existing forest management practices at that time.

EVALUATION OF THE HAZARD SYSTEM

Page's aphid damage hazard-rating system has been used for long-term management purposes to identify areas for stand improvement work conducted by both government and industrial agencies. Thinnings have been made to favor species other than balsam fir or to enhance the growth of balsam fir and thereby shorten its rotation period. Approximately 700 ha of immature stands have been thinned for these purposes. Controlled burning and various mechanical methods have been used on about 800 ha to destroy the balsam fir regenerating in high-hazard areas where the parent stands have been harvested. These treatments are followed by artificial seeding or planting to tree species other than balsam fir.

Conversion of stands to nonsusceptible species, as indicated above, has been recognized as the only way to prevent balsam woolly aphid damage. Unfortunately, it is unreasonable from both physical and economic points of view to expect this work to ever be done. It would be necessary to treat, then plant or seed 15,000 ha/year over an 80-year balsam fir rotation period (Munro 1976). However, it is generally agreed that stand conversion should be undertaken whenever it is possible (Hall and Richardson 1973 and Richardson 1979).

When the aphid damage hazard-rating system was proposed for integration into the forest management plans of various forest agencies, a list of cutting priorities was also recommended. The priorities in decreasing order of importance included

(1) Salvage dead stands before deterioration (within 5 years after death in Newfoundland).
(2) Remove severely infested stands.
(3) Remove severely damaged stands.
(4) Cut in high-hazard areas.
(5) Cut other areas.

Unfortunately, the aphid damage hazard-rating system has not been used by industry managers to dictate balsam fir harvesting plans. Instead, cutting policies have been determined first to deal with the age class distribution of the forest, which is unbalanced by a preponderance of overmature stands and second, to salvage-cut stands killed not only by the aphid but by other insect pests. Most damage by the aphid occurred during the 1960's; infestations had subsided by 1970 and have remained endemic in most areas. Extensive areas of balsam fir forest have also been killed by the hemlock looper (*Lambdina fiscellaria fiscellaria* [Guen.]) during the late 1960's and early 1970's and by the spruce budworm between 1975 and the present.

The attention of forest managers is presently focused on the spectacular and unprecedented losses occurring in the Island's balsam fir forests as a result of the current spruce budworm outbreak. The first budworm-caused mortality was reported in 1975, but in 1976 scattered dead trees were to be found throughout large areas of balsam fir forest. More than 50 percent of the total stand volume was dead in over 50,000 ha in 1977, in 66,000 ha in 1978, and in 97,000 ha in 1979. The total volume of wood involved in these stands in 1979 was estimated at 7,600,000 m^3 (Otvos and Moody 1978, Moody 1979 and 1980). Considerable mortality also occurred in less severely damaged stands. In 1979, budworm-killed trees were present in stands on 517,800 ha with a total volume of 38,400,000 m^3. This is more than 8 percent of the total softwood volume present on the Island. In addition, large increment losses from damaged but living trees are yet to be accounted for. These losses of increment and mortality are expected to continue to increase for at least 3 years following the termination of the outbreak--whenever this should occur.

Nearly all the areas where the balsam woolly aphid has occurred in the past are included within the boundaries of the spruce budworm outbreak. Many stands severely damaged by the aphid recovered from attack when the infestation subsided. However, despite recovery these stands apparently remained physiologically weakened because they were less able to withstand the effects of spruce budworm defoliation than were stands previously undamaged by the aphid. Only 2 or 3 years of severe budworm defoliation has killed aphid-damaged trees, whereas the mortality of other trees is generally expected after 4 to 5 consecutive years of severe defoliation (Otvos and Moody 1978, Moody 1979).

FUTURE PLANS

Data are presently being examined to indicate site and stand characteristics that will identify fir stands vulnerable to spruce budworm damage. Initially this will provide a budworm hazard-rating system similar to that available for the aphid. Next a system that jointly considers aphid and budworm hazard will hopefully be worked out. Such a system will identify areas particularly susceptible to both pests. Eventually a system that incorporates the hazard to all balsam fir insect pests may become available. Ideally the application of such an inclusive hazard-rating system would be the basis of an integrated pest management scheme to minimize forest losses.

LITERATURE CITED

Balch, R. E. 1952. Studies of the balsam woolly aphid, *Adelges piceae* (Ratz.) and its effect on balsam fir, *Abies balsamea* (L.) Mill. Dep. Agric. Can., Publ. 867. Fredericton, New Brunswick, Canada.

Clark, R. C., D. O. Greenbank, D. G. Bryant, and J.W.E. Harris. 1971. Biological control of forest pests in Canada, 1959-1968. *Adelges piceae* (Ratz.), balsam woolly aphid (Homoptera:Adelgidae). *In* Biological control programmes against insect and weeds in Canada. Commonwealth Inst. of Biol. Cont., Trinidad, Tech. Comm. No. 4:11-127.

Hall, J. P., and J. Richardson. 1973. Replacement of balsam fir by other softwood species in the forests of western Newfoundland. 29 p. Can. For. Serv., Inform. Rep. N-X-98.

Hopewell, W. W., and D. G. Bryant. 1969. Chemical control of *Adelges piceae* (Homoptera:Adelgidae) in Nfld. 1967. Can. Entomol. 101:1112-1114.

Jarvis, J. M., chairman. 1972. Report of the Committee on Forest Improvement and Protection to the Federal-Provincial Task Force on Forestry in Newfoundland. p. 113-114. St. John's, Newfoundland, Canada.

Moody, B. H. 1979. Spruce budworm damage assessment in Newfoundland in 1977 and 1978. 24 p. Can. For. Serv., Inform. Rep. N-X-173.

Moody, B. H. 1980. The status of the spruce budworm in Newfoundland in 1979. Can. For. Serv., Inform. Rep. N-X-190. 40 p.

Munro, J. 1976. Justification for consideration of a forest improvement program on the island of Newfoundland. *In* Proc. 1976 For. Improvement Workshop. [Gander, Newfoundland, Feb. 1976.] p. 162-173. Can. For. Serv., Newfoundland, Misc. Rep.

Otvos, I. S., and B. H. Moody. 1978. The spruce budworm in Newfoundland: histtory, status and control. 76 p. Can. For. Serv., Inform. Rep. N-X-150.

Page, G. 1975. The impact of balsam woolly aphid damage on balsam fir stands in Newfoundland. Can. J. For. Res. 5: 195-209.

Richardson, J. 1979. Stand conversion--replacing fir with spruce. *In* Proc. 1978 workshop: the future of fir. [Grandfalls, Newfoundland, Oct. 1978.] p. 31-35. Can. For. Serv., Newfoundland, Misc. Rep.

Schooley, H. O. 1980. The introduction, spread and occasional resurgence of the balsam woolly aphid in Newfoundland. *In* Proc. IUFRO Sec. S2.07.05 and .06 conference: Dispersal of forest insects; evaluation, theory and management implications. August 1979. Washington State Univ., Pullman. p. 116-127.

Schooley, H. O., and D. G. Bryant. 1978. The balsam woolly aphid in Newfoundland. 72 p. Can. For. Serv., Inform. Rep. N-X-160.

USE OF AVAILABLE RESOURCE DATA TO RATE STANDS FOR SOUTHERN PINE BEETLE RISK

Peter L. Lorio, Jr., and Robert A. Sommers[1]

Outbreaks of southern pine beetle (SPB), *Dendroctonus frontalis* Zimm., usually cause reflex reactions, including a flurry of direct control activities with at best doubtful benefit. Most of us agree that preventive medicine would be much preferable to the rough and ready first aid applied during outbreaks. The forest is like the human body; the better care you take now, the less trouble you'll have later.

Of course, forest managers can't afford continuous major commitments of time, money, and know-how to fight pest problems any more than we can commit all our time, money, and know-how to staying healthy. Somewhere there is a happy medium, a balance between input and return.

One way of approaching this balance in forest management is to use what we already know about potential problems in planning to avoid them. And even if we can't avoid them, we can fight them better when they happen. Routinely available forest inventory data, for example, could be used to rate stand susceptibility to SPB. Ratings could then be used, with traditional criteria, in selecting stands for regeneration and intermediate cuts. When outbreaks occur, control could be focused on high-risk stands.

We've been testing risk rating based on readily available resource data for several years. This approach requires no specially collected data. It makes planning to avoid or deal with a serious but sporadic pest problem part of the overall management planning process. And it helps forest managers at several levels keep the potential problem in mind.

THE PROCESS

Our approach to risk-rating stands for SPB follows Lorio's (1978) proposal to use available forest resource inventory data such as forest type, tree size and age, stand density, and site index. This method assumes that all southern pines are susceptible to attack, but loblolly and shortleaf are the primary host species; that lack of knowledge about SPB population dynamics prohibits useful predictions of infestations; that SPB food and habitat needs for abundant reproduction are related to recognizable stand characteristics; that stands favorable for SPB food and habitat are also resources whose loss would be costly; and that routine forest inventory data, used for many forest management purposes, can also be applied effectively to risk rating stands for SPB.

Continuous Inventory of Stand Conditions (CISC) is an automatic data processing system, used for National Forests in the South, that makes an up-to-date description of timber stands readily available. We used CISC data to risk-rate stands on the Kisatchie National Forest in Louisiana (fig. 1).

In risk-rating stands for SPB we use five data fields (numerals refer to position on chart; see fig. 1): forest type (3), stand condition class (4), method of cut (7), operability (8), and site index (12). *Forest type* is self explanatory. *Stand condition class* describes stands according to damage, quality, density, and age. Of the 15 classes, immature poletimber, immature sawtimber, and mature sawtimber are particularly important for risk rating. *Method of cut* describes the silvicultural treatment prescribed for the stand, such as clearcutting, thinning, or seed tree. *Operability* tells what kind and mixture of products are to be removed by the method of cut. To be operable on the Kisatchie National Forest, pine poletimber stands must yield at least 3 cords/acre, and sawtimber stands at least 800 fbm/acre (Scribner rule), under a silviculturally acceptable method of cut. Inoperable stands have such low timber volume that they have low risk of SPB outbreak even though individual trees might be very susceptible to attack.

Site index (10-ft classes) indicates the site's potential productivity. More productive sites can outperform poorer sites, producing larger trees and more of them per acre in less time. And these good sites, partly because they are characterized by moist or wet water regimes, have greater risk of SPB outbreaks (Lorio et al. 1972, Lorio and Sommers 1980).

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STAND PRESCRIPTION SUMMARY 2400-36 DOR: 2-23-80

NF 6 KISATCHIE WC 2 RD 1 PLANNING UNIT 2 COUNTY 43 COMP 16

CARD TYPE 1 (76)

1 STD NO.	2 LAND CLASS	3 FOR. TYPE	4 STAND COND	5 ACRES	6 INCL. ACRES	7 MOC	8 OPER	9 AGE YR.	10 WILD LIFE	11 MGT. TYPE	12 SITE IND.	13 CULT NEED	14 DATE WORK	15 CULT NEED	16 DATE WORK	17 CULT NEED	18 DATE WORK	19 CULT NEED	20 DATE WORK	21 FY & REGEN	22 LOCAL USE	23 RMKS	24 DOC. DATE	FILE CODE
01	500	962	11	0014	00	1	01	948	20	262	081	00	000	81	000	81	283	00	000	810	0000		0180	N.P.
02	500	962	11	0053	00	5	04	948	20	262	081	00	000	00	000	81	283	00	000	810	0000		0180	N.P.
03	500	231	10	0043	00	3	15	906	42	231	101	51	282	00	000	00	683	00	000	800	0000	H	0180	N.P.
04	500	944	12	0066	00	5	04	906	42	153	083	00	000	00	000	00	000	00	000	000	0000		0180	N.P.
05	500	231	12	0298	00	5	15	936	42	231	081	00	000	00	000	00	000	00	000	000	0000	M	0180	N.P.
06	500	953	11	0026	00	1	01	956	42	253	081	00	000	00	000	00	000	00	000	000	0000		0180	N.P.
07	500	231	12	0160	00	5	02	936	42	231	081	00	000	00	000	00	000	00	000	000	0000	M	0180	N.P.
08	500	969	11	0112	00	5	02	936	20	153	081	00	000	00	000	00	000	00	000	000	0000		0180	N.P.
09	500	946	12	0017	00	1	01	945	42	262	081	00	000	00	000	00	000	00	000	000	0000		0180	ERR.
10	500	231	10	0055	00	3	03	906	42	231	101	51	$\boxed{400}$	00	000	00	000	00	000	000	0000	H	0180	N.P.
11	500	231	12	0077	00	5	02	937	42	231	081	00	000	00	000	00	000	00	000	000	0000	M	0180	N.P.
12	500	231	10	0019	00	3	15	906	42	231	101	51	282	00	000	00	683	00	000	800	0000	H	0180	N.P.
13	500	231	10	0016	00	3	15	906	42	231	101	51	282	00	000	00	683	00	000	800	0000	H	0180	N.P.
14	500	231	10	0066	00	3	15	922	42	231	091	51	$\boxed{400}$	00	000	00	000	00	000	000	0000	H	0180	N.P.
15	500	831	11	0050	00	1	01	958	42	231	083	00	000	00	000	00	000	00	000	000	0000		0180	N.P.
16	500	846	11	0013	00	1	01	922	42	253	073	00	000	00	000	00	000	00	000	000	0000		0180	ERR.
17	500	213	11	0042	00	2	15	935	42	131	083	15	282	00	000	00	683	00	000	800	0000	M	0180	N.P.
18	500	231	10	0015	00	1	01	906	42	231	101	00	000	00	000	00	000	00	000	000	0000		0180	ERR.

CARD TYPE 2 (76) AREA CLASSIFICATION SUMMARY DOC. DATE 0180

WATER AREA 0000 STANDARD 1142 TOTAL COMPT. 1167

Figure 1.--Example of CISC data base used in stand risk-rating for SPB (Compartment 16 of the Catahoula Ranger District, Kisatchie National Forest). Coded data in fields 3, 4, 7, 8, and 12 are used in the rating process, and the high- and medium-risk stands are noted in field 23 (Remarks).

Subjective risk rating of stands follows a simple "yes or no" procedure (fig. 2). Kisatchie National Forest stands were rated this way with CISC data; high- and medium-risk stands were noted (remarks column 23, fig. 1). The area distribution of risk-rated stands can be shown easily on standard compartment maps commonly used for many management purposes (fig. 3).

RESULTS

Initial retrospective tests of stand risk rating with CISC data for the Catahoula Ranger District, based on 25 months of previously collected infestation data, showed that stands rated as high risk averaged 9.3, medium 6.8, and low 3.2 infestations per 1,000 acres. We extended the test by predicting stand risk, collecting 30 more months of SPB infestation data, and again determining the frequency of infestations per 1,000 acres in each risk-rating class (fig. 4). Frequency of in-

RISK RATING EXAMPLE

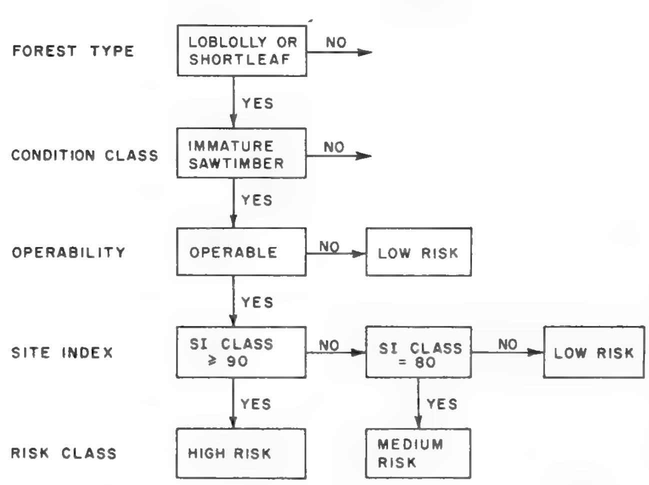
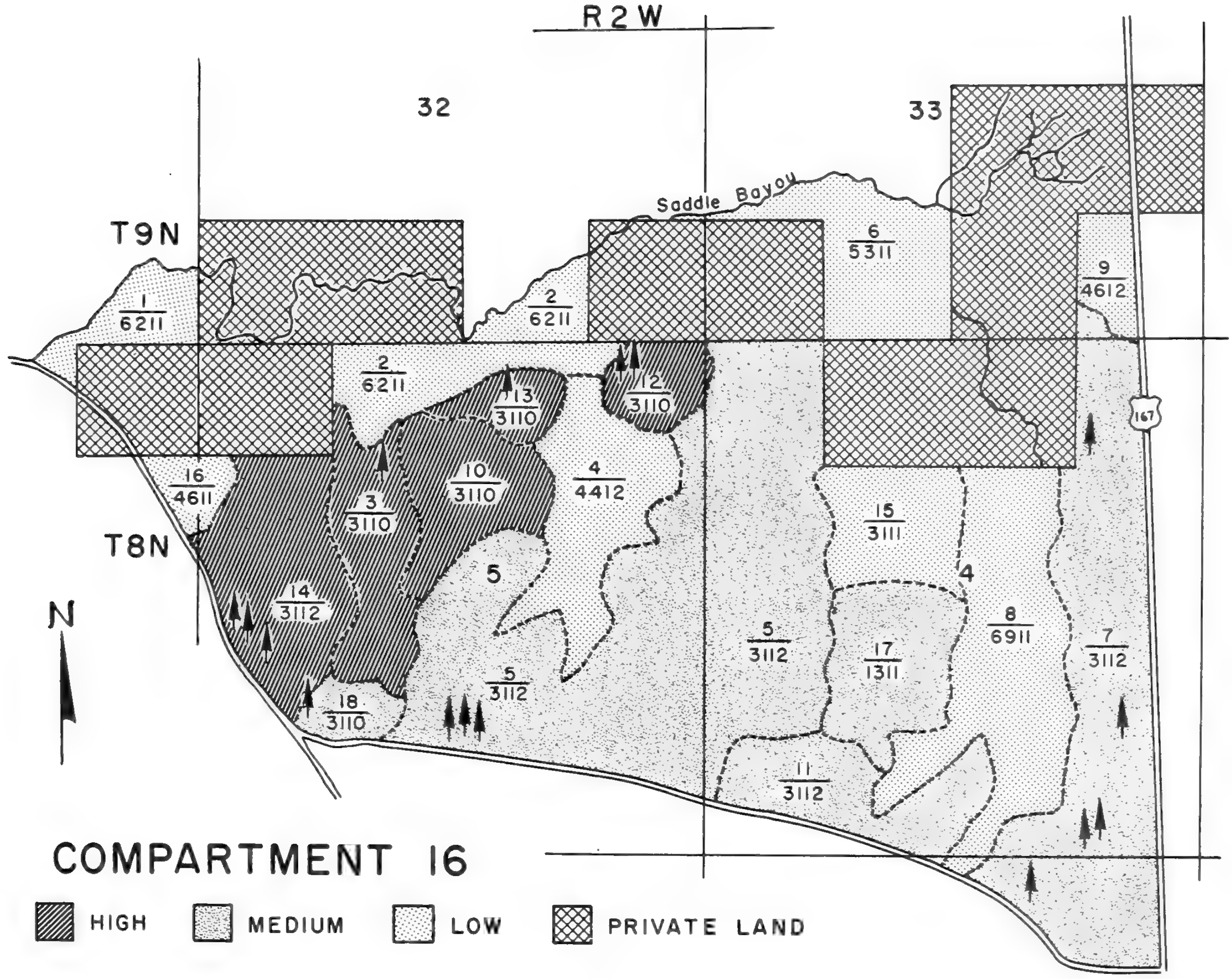


Figure 2.--Example of sequence used in subjective risk-rating of stands for SPB.



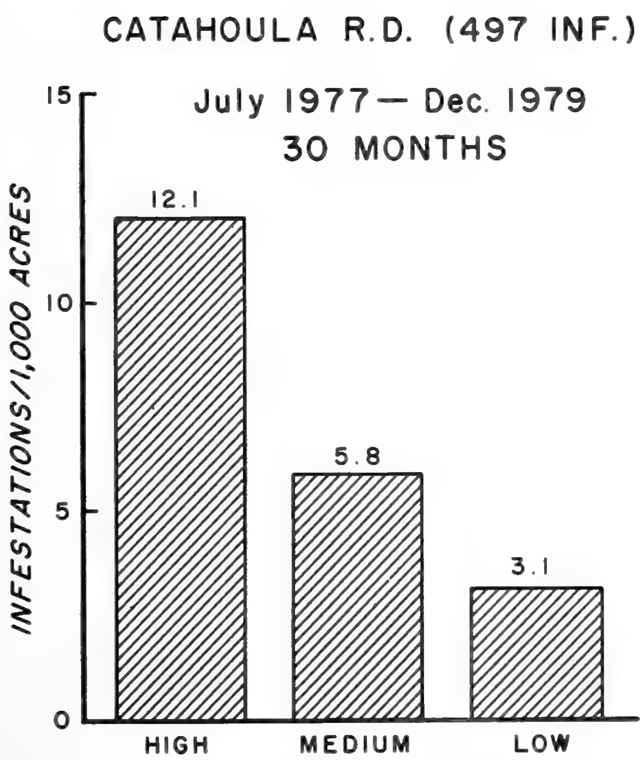


Figure 4.--Frequency of 497 SPB infestations on the Catahoula Ranger District, Kisatchie National Forest, by stand risk-rating for 30 months (July 1977 through December 1979).

Figure 3.--Map of Compartment 16, Catahoula Ranger District, Kisatchie National Forest, with stands grouped by risk-rating; the occurrence of SPB infestations is indicated by 🡅.

festation in high-risk classes was double that found in medium-risk classes and quadruple that in low-risk classes.

DISCUSSION AND CONCLUSIONS

Results of this study on more than 100,000 acres over 4.5 years strongly support use of available forest resource data for rating risks. Only 23 percent of the forest had high- and medium-risk stands (fig. 5), so forest managers probably could restrict most SPB considerations to about a fourth of the forest. And if specific potential problem stands are identified, as we have done with the CISC data in our example, they will remain identified in the data base throughout a management period. The forest manager, then, can easily weigh potential SPB problems in deciding which stands to thin or regenerate, what sequence of treatment to fol-

low during a cutting cycle, and what stands to monitor for potential problems. In cases where other considerations prohibit cutting, the associated risk of loss to SPB outbreak is explicit.

For example, stands 10 and 14 in figure 1 are prescribed for seed-tree cutting. But the digit 4 in data field 14 shows that cutting is deferred, probably because of coordination of several management goals. The SPB-risk codes in data field 23 (not currently part of the CISC data base) would serve as constant reminders of potential SPB problems in these stands. Without such easily available and explicit information, especially with the sporadic nature of SPB outbreaks, concern for SPB problems soon subsides as infestations decline.

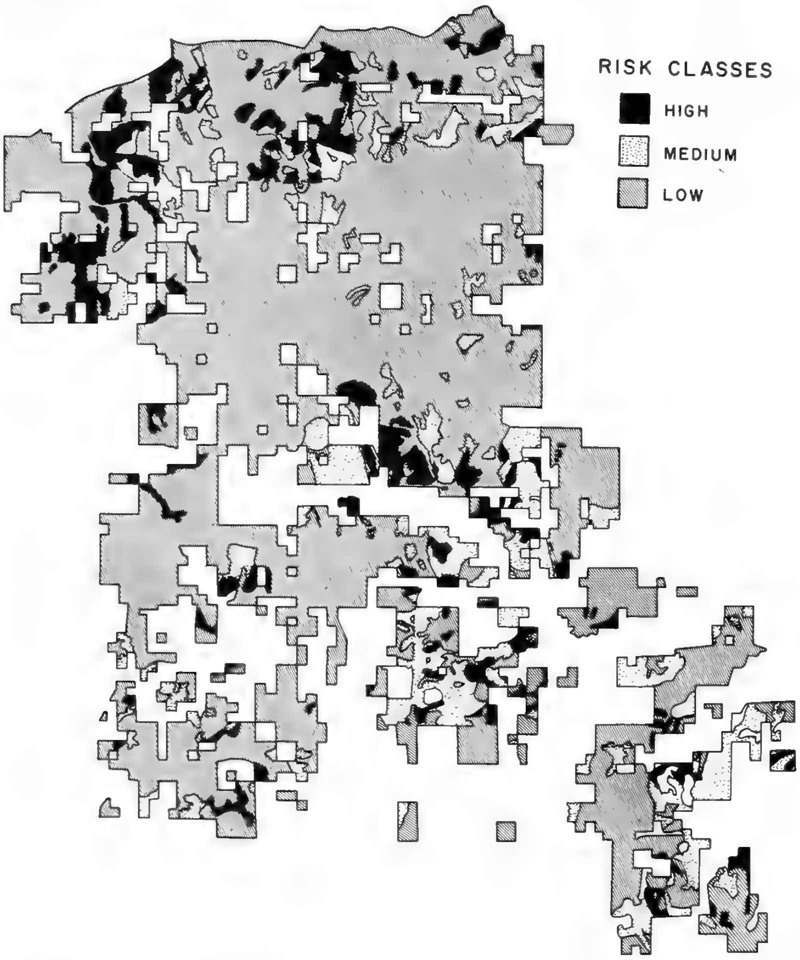


Figure 5.--Map of high, medium, and low SPB risk areas on the Catahoula Ranger District, Kisatchie National Forest, illustrates the relatively low total acreage and the spatial distribution of high-risk stands.

Tests and revisions of this approach to risk-rating stands are continuing on the Kisatchie National Forest. Because CISC does not include data on basal area, method of cut and operability are being used as broad indicators of density. Recent revisions of the CISC format will permit inclusion of basal area data (field 22, fig. 1) and entry of SPB risk-rating codes in field 23, if desired. Ideally, prescriptionists would risk-rate stands by applying criteria based on Forest Service, Region 8 thinning guides and results of a 25-month study of site and stand characteristics associated with SPB infestations (Lorio and Sommers 1980). This relatively painless procedure, a first step in dealing with an important but intermittent pest problem, would result in gradual updating and refining of stand risk-ratings as new silvicultural prescriptions are prepared.

LITERATURE CITED

Lorio, P. L., Jr. 1978. Developing stand risk classes for the southern pine beetle. 9 p. U.S. Dep. Agric. For. Serv., Res. Pap. SO-144. South. For. Exp. Stn., New Orleans, La.

Lorio, P. L., Jr., V. K. Howe, and C. N. Martin. 1972. Loblolly pine rooting varies with microrelief on wet sites. Ecology 53:1134-1140.

Lorio, P. L., Jr., and R. A. Sommers. 1980. Central Louisiana. *In* Site, stand, and host characteristics of southern pine beetle infestations. J. E. Coster and J. L. Searcy, eds. U.S. Dep. Agric. For. Serv., Tech. Bull 1612. Comb. For. Pest Res. Develop. Prog., Pineville, La.

DEVELOPMENT AND VALIDATION OF SYSTEMS FOR RATING THE SUSCEPTIBILITY OF NATURAL STANDS IN THE PIEDMONT OF GEORGIA TO ATTACK BY THE SOUTHERN PINE BEETLE

Roger P. Belanger, Richard L. Porterfield, and Charles E. Rowell[1]

Abstract.--This paper describes predictive models for rating the susceptibility of natural forest stands in the Upper Piedmont of Georgia to attack by the southern pine beetle. High-hazard stands are characterized by a higher proportion of shortleaf pine, slower radial growth, more clay in the surface and subsurface horizons, and a deeper surface soil than is representative of average host conditions in the area. Rating systems were validated in the Upper and Lower Piedmont of Georgia. They were effective when tested in the Upper Piedmont; they were poor predictors of stand susceptibility in the Lower Piedmont. Results are attributed to differences in stand conditions between the two provinces and insect populations at the time of model development and extrapolated testing. The paper presents guidelines for using the ranking systems and describes silvicultural practices that will reduce losses from the southern pine beetle.

Hazard-rating systems and cultural guidelines to reduce losses from the southern pine beetle (SPB), *Dendroctonus frontalis* Zimm., have been developed for several locations and different users throughout the South. Stand, site, and host tree conditions associated with beetle attacks are specific for the major geographic regions. Natural stands susceptible to SPB attack in the Gulf Coastal Plain are characterized by high stand densities, a large proportion of pine sawtimber and declining radial growth. Outbreaks occur more frequently in stands located on poorly drained, moist sites than on dry and droughty soils. Rating systems have been developed in the Coastal Plain for east Texas (Hicks et al. 1980, Mason 1980), the Kisatchie National Forest in Louisiana (Lorio 1978, Lorio and Sommers 1980), corporate timberland in Texas, Louisiana, and Mississippi (Kushmaul et al. 1979), and forests in south Arkansas (Ku et al. 1980).

Studies in the mountains of Georgia, North Carolina, and Tennessee showed that stands most subject to SPB attack were densely stocked, slow growing, and had a large proportion of overmature pine sawtimber (Belanger et al. 1979). Shortleaf pine *(Pinus echinata* Mill.) and pitch pine *(P. rigida* Mill.) were more susceptible to beetle attack than Virginia pine *(P. virginiana* Mill.) and loblolly pine *(P. taeda* L.). Site conditions were not associated with SPB infestations in the Southern Appalachians.

Stand and site conditions that lead to SPB attack can often be related to past land use, ownership patterns, and management objectives. Nowhere are these factors more evident than in the Piedmont of Georgia. At one time or another most of this land was in clean-cultivated crop production (Brender 1952). The sites, severely depleted by continuous cropping and erosion, were abandoned and have reverted back to forest.

SPB outbreaks, spread, and impacts have been extremely severe in this region (Price and Doggett 1978). Damage estimates from SPB outbreaks in Georgia during 1962 and 1972-76 totaled more than $25 million.

Preliminary studies have shown that beetle attacks in the Piedmont appear closely related to site and soil conditions (Belanger et al. 1977). Stand conditions, as in other regions, are also important in determining stand susceptibility. Research objectives were to (1) identify features of the stand associated with successful beetle attack and (2) use these variables to develop systems to rate the susceptibility of stands to SPB.

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METHODS

The Study Area

The Piedmont of Georgia can be divided into two distinct physiographic provinces (fig. 1). The Lower Piedmont has broad interstream areas of gently rolling hills. The Upper Piedmont is characterized by hilly topography and pronounced ridges. Study plots were located in both provinces. Loblolly pine and shortleaf pine are the predominant host species in the area. Approximately 80 percent of the forest resource in the Piedmont is located on nonindustrial private lands managed for timber and nontimber values.

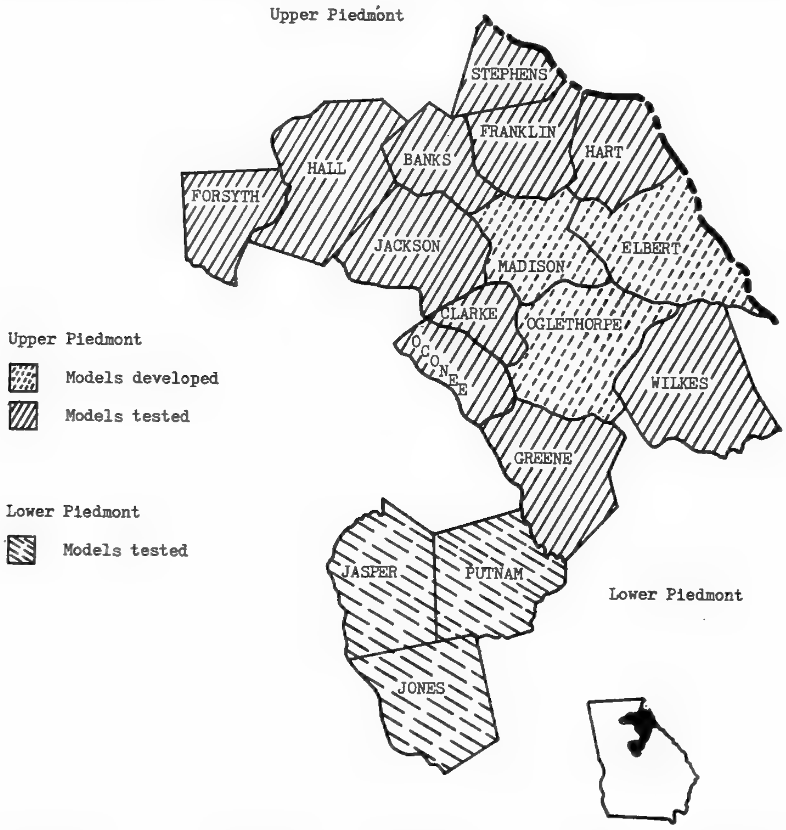

Figure 1.--Study counties for the Piedmont of Georgia.

Data from 58 stands attacked by the SPB and 139 baseline stands were used to develop the rating systems. Study plots were located in Madison, Elbert, and Oglethorpe Counties, Georgia. These counties are in the Upper Piedmont and contain approximately 1,150 km^2 of host type.

An additional data base--64 attacked stands in 11 other Upper Piedmont counties and 38 attacked stands in 3 lower Piedmont counties--was used to test the application of local rating systems over a large area. Plots were sampled in the Upper Piedmont from 1975 through 1977. SPB populations in Georgia during 1975 were in decline from epidemic conditions; beetle populations were endemic during 1976 and 1977. Plots were sampled during 1979 in the Lower Piedmont. Beetle populations in this area had risen to epidemic levels with more than 16 infestations per hectare of host type.

Field Procedure

The Georgia Forestry Commission, the Chattahoochee-Oconee National Forests, and ground-survey crews provided location of attacked stands. Ground crews located plot center in attacked stands 1.5 m north of what could best be determined as the first infested tree. We randomly selected baseline plots, used to estimate average forest conditions within the study area, from type maps developed using LANDSAT remote sensing images. Plot center for baseline plots was established from preestablished points transferred from the type maps to aerial photos. We did not include in the survey plantations and stands that had been disturbed within the last 5 years.

Field crews estimated size of the SPB outbreak and counted the total number of beetle-killed trees in attacked stands. Workers used a 10-factor prism to locate measurement trees. The following characteristics were recorded for each "in" tree: (1) species, (2) status--live or dead (SPB killed), (3) diameter at breast height (1.37 m above ground level), (4) total height, and (5) height to live crown.

Additional measurements were taken on three to six dominant or codominant trees on each plot: (6) age--determined from increment cores taken at breast height, (7) bark thickness--measurements for maximum thickness (from the ridges) and minimum thickness (from the base of the fissures), (8) radial growth--from increment at breast height determined for the last two 5-year periods.

These measurements were used to determine the following stand characteristics: (9) site index--calculated from age and height (Schumacher and Coile 1960), (10) stand density--the number of trees per hectare obtained from d.b.h. measurements, (11) basal area--partitioned into that attributable to pine and hardwood species, (12) estimate of the percent coverage of the area by woody understory vegetation.

Site variables measured included (13) percent slope, (14) aspect (azimuth), and (15) depth of the *A* horizon.

Samples of the surface soil (0-15 cm) and subsoil (B_2 horizon) were taken for laboratory analyses. All soil samples were air dried, rolled, and passed through a 2-mm sieve in preparation for testing. Lab workers determined particle size distribution by the hydrometer method; they measured pH using a glass electrode in a 1:1 soil-to-water mixture.

Developing the Models

We used discriminant analyses to develop models for ranking the susceptibility of stands to SPB attack. The stepwise procedure selected those variables that most enhanced discrimination between attacked and baseline stands until no significant improvements were realized from the addition of more variables. Positive or negative coefficients were affixed to each site/stand variable depending on the direction of its influences on susceptibility. The resulting equation predicts a discriminant score, which can be used to rank the relative susceptibility of a stand. A positive score indicates low susceptibility to beetle attack; a negative value indicates higher susceptibility to beetle attack.

Validating the Models

We validated the discriminant models by their accuracy for correctly classifying (1) study plots used in model development, (2) infested plots surveyed in the 11 other Upper Piedmont counties, and (3) infested plots surveyed in the 3 Lower Piedmont counties. High, moderate, and low susceptibility classifications were determined for the different systems. Need for silvicultural attention was related to susceptibility scores and classifications.

RESULTS

Stands attacked by the SPB are characterized by slower radial growth, more clay and less silt in the surface and subsurface horizons, and a deeper surface soil than baseline plots (table 1). There was little difference in pine basal area, age, or site index between the two study populations. The hardwood component and amount of understory vegetation were significantly lower for attacked than baseline stands: basal areas ≧ 25 m^2/ha oc-

Table 1.--Variable means for attacked and baseline plots--natural, undisturbed stands, Piedmont of Georgia

Variable	Units	Attacked	Baseline	Statistical differences[1]
		---------Mean---------		
Slope	%	10.5	11.3	N.S.
Aspect (azimuth)	degrees	206.6	190.8	N.S.
Surface sand	%	57.1	60.6	0.05
Surface silt	%	18.2	20.6	0.05
Surface clay	%	24.7	18.8	0.01
Surface pH		5.1	5.1	N.S.
Surface soil depth	cm	10.3	7.0	0.01
Subsoil sand	%	40.3	42.0	N.S.
Subsoil silt	%	16.0	19.0	0.01
Subsoil clay	%	43.8	39.0	0.05
Subsoil pH		5.2	5.3	0.05
Pine basal area	m^2/ha	22.5	23.1	N.S.
Hardwood basal area	m^2/ha	3.8	5.4	0.05
Total basal area	m^2/ha	26.3	28.5	N.S.
Stand understory	%	46.4	57.3	0.01
Age	yr	33.4	35.3	N.S.
Density	trees/ha	1687.8	1908.6	N.S.
Site index (50 yr)	m	21.9	22.0	N.S.
Average d.b.h. ("in" trees)	cm	21.1	22.6	N.S.
SPB-killed trees	per spot	54.3		
Spot size	ha	0.3		
Average bark--fissure	cm	1.3	1.5	0.01
Average bark--ridge	cm	2.3	2.3	N.S.
Average radial growth (0-5 yr)	mm	11.6	14.1	0.01
Average radial growth (6-10 yr)	mm	15.3	18.0	0.01
Average live crown	%	41.4	40.1	N.S.
Percent shortleaf (total pine)		68.6	44.5	0.01
Percent loblolly (total pine)		31.4	55.5	0.01

[1] N.S. = Nonsignificant
0.05 = Level of probability
0.01 = Level of probability

curred on 64 percent of the attacked plots, and 66 percent of the baseline plots. Shortleaf pine appears to be more susceptible to SPB attack than loblolly pine. Attacked stands were predominantly shortleaf pine, whereas baseline plots contained mostly loblolly pine. Most of these variables are represented in the hazard ranking models.

Measures of Stand Susceptibility

Two hazard-rating systems were developed for the Piedmont of Georgia. The first, called the best model, included all variables in the stepwise procedures. The number of variables needed to significantly distinguish the susceptibility of host stands has been reduced from 14 to 6.

Best Model

Discriminant score = + 2.38664 - 0.10111 (SURCLAY)

- 0.08016 (SURDEPTH) + 0.07842 (SOIL1)

+ 0.05551 (AVERAD) - 0.02645 (LIVECRWN)

+ 0.00530 (PERLOB)

where

SURCLAY = Percent clay in surface (0-15 cm) horizon

SURDEPTH = Depth (cm) of A horizon

SOIL1 = Percent clay per cm A horizon depth

AVERAD = Radial growth (mm) of dominant and codominant pines (most recent 0 to 5 years)

LIVECRWN = Percent live crown (average of all pines)

PERLOB = Percent loblolly in total pine component

Standardized discriminant function coefficients show that site characteristics were the most important variables contributing to classification. Stands with discriminant scores of ≦ -0.2835 were classified as most likely to be attacked; higher scores indicate less likelihood of SPB attack.

The best model correctly classified 86 percent of the attacked plots and 83 percent of the baseline plots used in its development. Overall accuracy was 84 percent (165/197); see table 2.

The second rating system is a land manager's model that includes variables that are easily measured or contained in existing inventories. In this model, the number of variables needed to significantly distinguish the susceptibility of host stands has been reduced to four.

Table 2.--Correctness of classifications by the best model

Actual status	Total plots	Predicted status: Attacked	Predicted status: Baseline
Attacked	58	50	8
Baseline	139	24	115

Land Manager's Model

Discriminant score = +1.24082

-0.12903 (SURDEPTH) + 0.10006 (AVERAD)

-0.04829 (LIVECRWN) + 0.00941 (PERLOB)

Depth of the *A* horizon was the most important variable contributing to classification. Plots with scores ≦ -0.1968 were classified as attacked, while plots with scores above this level were classified as baseline.

The land manager's model correctly classified 72 percent of the attacked plots and 70 percent of baseline plots. Overall accuracy was 71 percent (139/197). This is a 13 percent loss in efficiency compared with the best model (see table 3).

Table 3.--Correctness of classifications by the land manager's model

Actual status	Total plots	Predicted status: Attacked	Predicted status: Baseline
Attacked	58	42	16
Baseline	139	42	97

Using the Models

Table 4 shows how discriminant scores were computed for five study stands using the land manager's model. Coefficients (A) for the significant variables were multiplied by actual stand values (B) to obtain a discriminant product (A × B). The net discriminant score (adding the products including signs) indicates the direction and degree of susceptibility. The average value for all attacked plots was -0.6753; the average score for baseline plots was 0.2818.

Table 4.--Discriminant score computation and susceptibility ranking for five natural stands

Stepwise selection model		Stand values for each variable for plots 1 through 5					Products-coefficient multiplied by variable value				
Variable	Coefficient	1	2	3	4	5	1	2	3	4	5
	---A---	-----------B----------					------------------A × B------------------				
Depth "A" horizon (cm)	-0.12903	12	10	8	7	7	-1.5484	-1.2903	-1.0322	-0.9032	-0.9032
Radial growth (0-5 yr) mm	0.10006	10	11	13	12	14	1.0006	1.1007	1.3008	1.2007	1.4008
Live crown (%)	-0.04829	49	45	42	39	38	-2.3662	-2.1730	-2.0282	-1.8833	-1.8350
Loblolly (% of pines)	0.00941	30	42	50	68	80	0.2823	0.3952	0.4705	0.6399	0.7528
						Constant term	1.2408	1.2408	1.2408	1.2408	1.2408
						Discriminant score (constant included)	-1.3909	-0.7266	-0.0483	-0.2949	0.6562
						Stand ranking based on discriminant score (1 = most susceptible)	1	2	3	4	5

Discriminant score = 1.2408 - 0.12903 (SURDEPTH) + 0.10006 (AVERAD) - 0.04829 (LIVECROWN) + 0.00941 (PERLOB).

Discriminate scores were also used to indicate general hazard rankings and the need for cultural treatments (fig. 2).

Stands 1 and 2 (table 4) are high-hazard stands and should receive immediate silvicultural attention. Cultural treatments should also be scheduled for stand 3. Measures to prevent attacks by the SPB can be deferred in stands 4 and 5. The hazard-ranking system is somewhat conservative, favoring cultural treatments at the 0.0 score rather than the actual -0.1968 midpoint value.

Extrapolated Testing of the Models

The best model and land manager's model were used to classify attacked plots

Hazard Ranking

	HIGH	MODERATE	LOW	
Discriminant	-0.5	0	+0.5	Score
	Needed		Not needed	

Cultural Treatments

Figure 2.--General hazard rankings and the need for cultural treatments based on discriminant scores.

sampled in the other Upper Piedmont counties. The best model classified 86 percent of the plots correctly; ratings for the land manager's model were 82 percent accurate. The land manager's model is more readily applicable yet only slightly lower in predictive ability than the best model.

The land manager's model was also used to classify 38 attacked stands sampled in the Lower Piedmont of Georgia. Only 39 percent of these plots were classified correctly. Differences in the predictive ability of the model for the two subregions appear related to (1) forest conditions between the Upper and Lower Piedmont, and (2) levels of SPB activity at the time of model development and extrapolated testing.

Table 5 lists stand and site conditions measured in SPB-attacked stands in the Upper and Lower Piedmont of Georgia. Attacked stands in the Lower Piedmont were characterized by a larger proportion of loblolly pine, more sawtimber, slower growth, and higher basal areas than attacked stands in the Upper Piedmont. Conditions associated with infestations in the Lower Piedmont closely resemble those reported for the Gulf Coastal Plain (Lorio 1978, Kushmaul et al. 1979, Hicks et al. 1980). Stand-rating systems developed

Table 5.--Stand and site characteristics of SPB-attacked stands in the Upper and Lower Piedmont of Georgia

Variable	Units	Piedmont: Upper — Elbert, Madison, Oglethorpe Co.	Piedmont: Upper — 14 Study Co.	Piedmont: Lower — Jones, Jasper, Putnam Co.
Pine basal area	m^2/ha	22.5	23.1	23.1
Hardwood basal area	m^2/ha	3.8	3.8	6.1
Total basal area	m^2/ha	26.3	27.0	29.2
Average d.b.h.	cm	21.1	21.6	30.7
Average height	m	13.7	--	20.7
Average live crown	%	41.4	--	38.0
Average radial growth (0-5 yr)	mm	11.6	11.5	6.9
Age	yr	33.4	33.8	--
% Shortleaf (total pine)		69	--	47
% Loblolly (total pine)		31	--	53
Surface soil depth	cm	10.3	10.7	5.9

for the Coastal Plain may be more applicable than Upper Piedmont models in predicting the susceptibility of Lower Piedmont stands to SPB attack.

Southern pine beetle activity was low during the development and validation of the rating models in the Upper Piedmont (fig. 3). Beetle activity was extremely high while we tested the effectiveness of the land manager's model in the Lower Piedmont. Any preference by the SPB for particular stand conditions may be masked by the large number of infestations and spot spread associated with epidemic beetle populations.

It is still unclear whether differences in stand conditions or beetle populations limit the extrapolated use of risk-rating models. These unknowns could

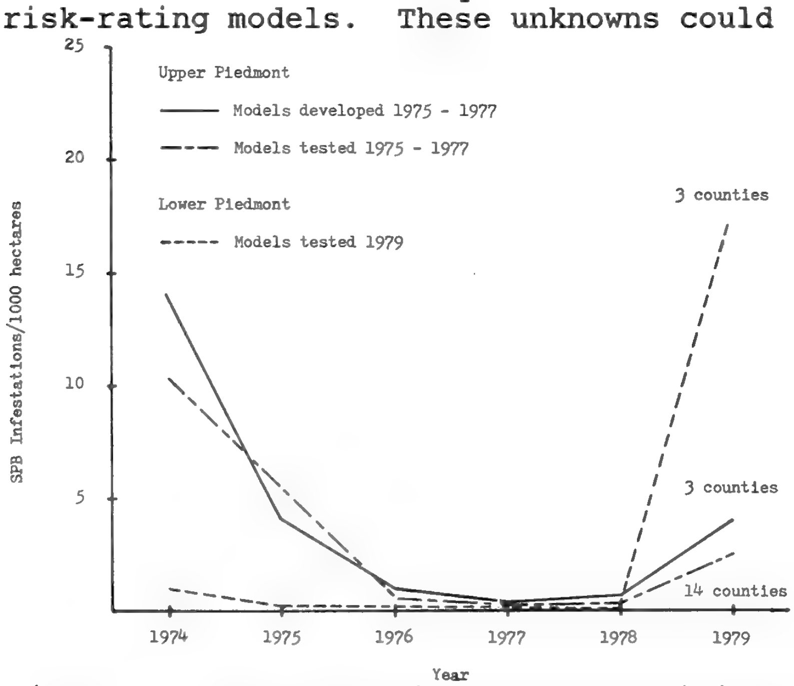

Figure 3.--Southern pine beetle activity in the Upper and Lower Piedmont of Georgia, 1975-79.

be clarified for the Piedmont models by (1) testing the land manager's model in the Upper Piedmont when SPB populations are high, and (2) testing the land manager's model in the Lower Piedmont when beetle populations are low. Coastal Plain models should also be tested in the Lower Piedmont during periods of high and low beetle activity.

REDUCING LOSSES FROM THE SPB

Results show that pine stands in the Upper Piedmont of Georgia which are highly susceptible to SPB attack are characterized by a large percentage of shortleaf pine, slow radial growth during the last 10 years, and a high clay content in the surface and subsurface horizons. These variables have to be considered collectively in determining a possible cause-and-effect relationship. Clay soils restrict expansive root development by limiting aeration and infiltration of water. These conditions often contribute to the onset of root diseases and the killing of small roots. Deteriorating root systems cause a sustained reduction in radial growth and severe physiological stress on trees during periods of drought or excess moisture. "Locus" trees--those first attacked and preferred by the SPB--appear to be dominant and codominant trees with large live crown ratios and root systems in incipient stages of decline. Trees in advanced stages of decline are seldom killed by the SPB. Moisture and nutrient supply in these trees may not be adequate for successful attack or brood production.

Silvicultural techniques provide means of reducing the susceptibility of

high-risk stands in the Piedmont of Georgia to SPB attack. Managing species composition should be a first consideration to improve stand conditions. Regeneration methods and intermediate cuttings should favor loblolly pine whenever possible. Loblolly pine is significantly more resistant to beetle attack in the Georgia Piedmont, grows faster, and is less susceptible to littleleaf disease than shortleaf pine.

A combination of thinning, improvement cutting, and salvage cutting can be used in young stands to control basal area and density levels. Two or three intermediate treatments are recommended to maintain stand vigor and rapid growth. Severe thinning in the Piedmont can result in excess losses due to glaze storms. Stands that are in advanced stages of decline should be scheduled for regeneration.

Managers should select harvesting equipment that minimizes damage to residual trees during cultural treatments. Excess logging debris, fresh wounds on trees, and damage to root systems often compound forest pest problems. How cultural operations are conducted to reduce losses from the SPB may be more important than what is done.

Another preventive measure that may be attractive to small, nonindustrial owners is managing pine and hardwoods in mixture. In this study, the amounts of hardwoods and understory vegetation were significantly less in attacked stands than in baseline stands. Belanger et al. (1979) found that infestations in the Southern Appalachians were also more prevalent in pine stands than in mixtures of pine and hardwoods. Management of mixed species may be particularly suited where nontimber values are a primary objective. A mixed and layered stand supports diverse and dense wildlife populations, can be esthetically pleasing, and contributes toward a gradual improvement of poor sites.

Little can be done to make immediate or significant improvements in soil and site characteristics associated with high-risk stands. These sites have a high erosion potential and require careful tending. Cultural practices should disturb these soils as little as possible. Burning and the application of selected herbicides can be successfully used to ready sites for regeneration and control hardwood competition. Intensive site preparation and cultivation with heavy equipment are recommended only where soils and slopes are suited for these practices.

Forest conditions, host types, and ownership objectives are varied in the Piedmont of Georgia. Much of this diversity is the result as well as the cause of SPB infestations. A reduction in land and timber values is the common consequence of beetle attacks. Host management, however, provides the opportunity to reduce the probability of SPB infestations and to minimize losses should outbreaks occur. Primary emphasis should be given to high-hazard stands that contribute significantly to management objectives. Hazard-ranking systems provide the means to identify problem conditions. Cultural treatments provide the means to correct them.

LITERATURE CITED

Belanger, R. P., G. E. Hatchell, and G.E. Moore. 1977. Soil and stand characteristics related to southern pine beetle infestations: a progress report for Georgia and North Carolina. Proc. Sixth South. Forest Soils Workshop, Charleston, S.C. Oct. 19-21, 1976. p. 99-107. U.S. Dep. Agric. For. Serv., Southeast. Area, State and Private Forestry, Atlanta, Ga.

Belanger, R. P., E. A. Osgood, and G. E. Hatchell. 1979. Stand, soil, and site characteristics associated with southern pine beetle infestations in the Southern Appalachians. 7 p. U.S. Dep. Agric. For. Serv., Res. Pap. SE-198. Southeast. For. Exp. Stn., Asheville, N.C.

Brender, E. V. 1952. From forest to farm to forest again. Am. For. 58(1):24-25, *ff*.

Hicks, R. R., Jr., J. E. Howard, K. G. Watterston, and J. E. Coster. 1980. Rating forest stand susceptibility to southern pine beetle in east Texas. For. Ecol. Manage. 2:269-283.

Ku, T. T., J. M. Sweeney, and V. B. Shelburne. 1980. Site and stand conditions associated with southern pine beetle outbreaks in Arkansas-hazard rating system. South. J. Appl. For. 4:103-106.

Kushmaul, R. J., M. D. Cain, C. E. Rowell, and R. L. Porterfield. 1979. Stand and site conditions related to southern pine beetle susceptibility. For. Sci. 25:656-664.

Lorio, P. L., Jr. 1978. Developing stand risk classes for the southern pine beetle. 9. p. U.S. Dep. Agric. For. Serv., Res. Pap. SO-144. South. For. Exp. Stn., New Orleans, La.

Lorio, P. L., Jr., and R. A. Sommers. 1981. Stand risk classification for the southern pine beetle with available resource data. *In* Hazard-

rating systems in forest insect pest management: symposium proceedings. [Athens, Ga., July 1980.] R. L. Hedden, S. J. Barras, and J. E. Coster, coords. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-27.

Mason, G. N., R. R. Hicks, Jr., C. M. Bryant V., M. L. Mathews, D. L. Kulhavy, and J. E. Howard. 1981. Rating Southern Pine Beetle Hazard by Aerial Photography. *In* Hazard-rating systems in forest insect pest management: symposium proceedings. [Athens, Ga., July 1980.] R. L. Hedden, S. J. Barras, and J. E. Coster, coords. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-27.

Price, T. S., and C. Doggett. 1978. A history of southern pine beetle outbreaks in the eastern United States. 31 p. Georgia Forestry Commission, Macon, Ga.

Schumacher, F. X., and T. S. Coile. 1960. Growth and yields of natural stands of the southern pines. 97 p. T.S. Coile, Inc., Durham, N.C.

SAMPLING AND ANALYTICAL METHODS FOR DEVELOPING

RISK-RATING SYSTEMS FOR FOREST PESTS[1]

Albert R. Stage and David A. Hamilton, Jr.[2]

Abstract.--Risk-rating systems for forest pests usually define a scale of relative frequencies of damage. For some pests, it may be useful to estimate expected pest-induced damage in two steps: (1) predict likelihood of the pest population abruptly increasing to high densities, and (2) predict extent of damage caused by the pest at high densities.

When developing pest hazard-rating systems, investigators commonly overlook two essential features: first, data must be obtained with quantifiable sampling probabilities from a well-defined population; and second, analytical methods must properly use both the parameters of the sample design and the data collected in the sample. So devised, the rating system may be useful for integrating pest management decisions into the wider context of forest management planning. Rating systems for Douglas-fir tussock moth damage are offered as examples.

Increasing competition for resources--both people and money--to manage forests forces more quantitative evaluation of consequences of management action. And the scope of the competition has widened. Where once pest management activities were only competing with other pest management activities, we now must justify allocations to pest management vis-à-vis fire management and stand regeneration and improvement. And in common with these other fields of management, investments must be justified on the basis of their contribution to the flow of benefits from the forest.

To guide the decisions that allocate management resources, pest managers have called for development of risk-rating systems. Existing systems have used several kinds of scales for rating stands and their environment. The simplest scale divides stands into two classes: susceptible or not susceptible. More definitive systems offer scales useful for arraying stands in increasing order of risk, but which are not useful for interpreting the distances between any pair of stands on the scale. Such scales are called ordinal. Although the rankings might be useful for determining priorities for treatment, they would not be useful for deciding how many, if any, of the stands *should* be treated, or whether alternative treatments should be used.

Most useful are continuous scales that permit quantitative interpretation of the interval between two stands on the scale. For example, a probability scale can represent the odds that a stand will be affected, or a volume scale can predict how much loss a particular stand might be expected to experience. Volume loss is an alluring scale. Superficially, it seems to be just what a manager can understand and use. Unfortunately, this utility is real only if the stand is to be immediately harvested--and then the "lost" volume may be salvable anyhow.

Indeed, the most powerful application of any risk-rating system is to stratify stands such that there are maximum differences between strata with respect to odds of mortality, reduction of increment, and reduction of existing volumes per tree. With estimates of these rates, effects of pest management can be calculated commensurate with effects on forest values of any other silvicultural treatments.

The structure of a risk-rating system can affect its usefulness for each of the many kinds of decisions a pest manager must face. How to deploy detection surveys, when and where to treat and by which methods, are all decisions that could benefit from information supplied from a risk-rating system. As we have learned from fire danger research, however, an index that describes in one number "the likelihood that a fire will start, spread, and do damage" is less useful than separate treatment of each of the phases of the damaging event. How the overall risk-rating system is divided into phases and the choice of scales to describe each

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phase determines both the methods that must be used for analysis and the sampling methods that must be used to provide data for the analysis.

A key attribute of all risk-rating procedures is that they provide information about systems that contain large random elements. Entomologists and pathologists have sought to discover deterministic components that explain the overall variation--with some success for a few pests. Nevertheless, inevitably some residual random variation defies explanation, and it must be taken into account in evaluating treatments and in the decisions and strategies embodied in management plans for the forest. The randomness is distributed in both time and space. For most every condition under which a pest episode is observed to occur, we can find places with apparently identical conditions where the pest episode fails to occur within a specified time interval. Predicting the relative frequencies of these two outcomes, given different conditions, is the major objective of many systems for risk rating. However, in some methods of analysis the relative frequencies are not explicitly represented. Instead, the effects of the relative frequencies are implicit in the calculation of average levels of damage. In other systems that use classification methods, the randomness is represented in part by the rates of misclassification. Or, in yet other systems, the probability distributions of the pest events are explicitly estimated by conditional probability models. Crucial to the validity of any of these alternatives is their being founded on a well-defined random sample.

In some situations, however, considerable efficiency can be gained if sampling locations are selected to fill cells in an appropriate experimental design. When this procedure is followed, sampling locations must be selected at random within each of the cells of the design matrix. For example, if one wishes to estimate the effect of stand density, observations might be selected so as to obtain equal numbers of sample locations in each defined density class. Sample locations would have to be selected at random from those locations in the population that are included in each density class.

Unfortunately, some forms of analysis used in developing risk-rating systems, such as discriminant analysis, place additional, more severe restrictions on the sampling design. When discriminant analysis is used, no stratification or experimental design based on the independent variables may be used in the sample selection process unless the relative sampling probabilities between cells or strata can be determined. This information may be obtained only if a completely enumerated sampling frame exists or if additional sampling is done.

RECOMMENDED PROCEDURES

For a number of major pests we have found it useful to separate procedures for predicting the initiation of a pest episode from procedures for predicting the subsequent level of damage (trees killed, volume lost, vegetational changes). For example, in our work with Heller and Miller (1976) on the Douglas-fir tussock moth *(Orgyia pseudotsugata* [Mc D.]), no significant predictors could be identified when degree of defoliation was defined as a continuous variable ranging from 0 percent to 100 percent. But, when the damage was described dichotomously by presence or absence of visible defoliation, then significant predictors became identifiable. Subsequent damage could then be estimated by a conditional outbreak model (Colbert 1978). Likewise, Daniels and others (1976) argue for separating predictions of incidence from severity. Factoring the estimation of losses in this way has several advantages. First, we can use different sampling methods for the two phases. Second, the statistical distributions are more tractable so that hypothesis-testing is simplified. Third, the resulting model structure is more closely identified with events and processes in the real system. Procedures for combining these two phases leading to evaluation of management options have been described (Stage 1975, Talerico and others 1978).

Our approach to risk-rating forest stands for pest damage requires inferences about two phases of the damaging process.

1. The relative frequencies of occurrence of the outcomes of the random event of interest in a specified time period. Examples of the random event include a tree either being killed or not being killed by bark beetles, or the presence or absence of visible defoliation. Of particular interest is the relationship between relative frequencies of the event and tree, stand, and site attributes.

2. The amount of damage to expect for each outcome of the random event. The amount of damage is expressed as a function of tree, stand, and site attributes. Damage can be defined as mortality, growth reduction, or both.

Sampling methods and analysis techniques for each of these two phases are outlined in the following sections.

PHASE I--ESTIMATING RELATIVE FREQUENCIES

Sampling Requirements

A sampling procedure for constructing a forest pest risk-rating system must meet two key design requirements. First, the sampling design must permit unbiased estimates of the relative frequencies of occurrence of the random event (dependent variable). Second, the sampling design must provide a sound basis for inferring the distribution of the variables that condition the occurrence of the random events. For example, the random event might be the occurrence of a specified defoliation level in a particular stand. The conditioning variables can include characteristics of the tree population, of the site, and of the climate. Choice among these variables would depend on the definition of the random event being represented. Where outbreaks of contagious pests are being evaluated, the spatial distribution of these conditioning variables must also be represented. However, weather patterns affecting large areas may cause synchronous variations in pest populations that are difficult to separate from contagion due to actual migration of pest populations.

To estimate relative frequencies, the samples must include both the occurrence and nonoccurrence of the random event. However, relative frequencies of these two outcomes in the sample data determine the probability of the event *only* if the sampling design is well defined. All too commonly, extensive data are collected to describe the conditions where the pest episode did, in fact, occur. But corresponding data representing the nonoccurrence of the event are seldom available. For a fortunate few (Lorio 1978), the availability of complete inventories may obviate the need for sampling.

The first step in the process of gathering data is to define the ecological limits of the population to be described. The limits may depend on where the pest episode definitely cannot occur. For obligate pests, an obvious limitation is the absence of the host. Another limit might be an extreme of elevation. Above all, the limits should *not* be defined by the extent of the current *pest* damage.

The next step is to select the number and definitions of mutually exclusive and completely exhaustive states or outcomes that are to be described for each sampling unit. For example, if the system being studied is a pine bark beetle and its potential host trees, outcomes of a tree might be defined as (1) unattacked; (2) attacked, but beetles repulsed; and (3) attacked and killed. In the simplest case, there would be two outcomes: a live tree *v.* a dead tree, or an infested stand *v.* an uninfested stand.

The third step of the sampling design is to define the variables that are expected to influence the probabilities with which the event we are describing will occur. In the case of pine bark beetle, physical and edaphic descriptions of the site, vigor and stage of development of the host, stand density, and growth rates are all variables that might influence the relative probability of each outcome.

To represent contagion, cluster sampling or additional context variables describing site, stand, and pest population conditions in surrounding areas should be considered. The spread of the cluster, or the area included in the context variable, will depend on the characteristics of particular pests.

The final, and most often overlooked step in designing a pest-monitoring system is to define the way in which a sampling probability is to be assigned to each sample unit. Although many sampling designs applied in forestry use equal probabilities for selecting each unit, arbitrary assignment of sampling probabilities may come closer to meeting needs for information (Stage 1974). Rare events, in particular, can be sampled more efficiently by an unequal probability design. For example, to estimate annual mortality rates that are expected to average about half of one percent, we would not want to measure and record 200 live trees for each one that, on the average, would have died in the year's time. Instead, a more efficient design would be to sample in such a way that each dead tree has a sampling probability that is some fixed multiple of the sampling probability of the live trees. For example, we have used a ratio of 14:1 to estimate mortality rates in northern Idaho. This ratio of sampling probabilities can be entered into the calculation of a conditional probability model (Hamilton 1974) to obtain unbiased estimates of the event probabilities. Occasionally, it may be possible to calculate the ratio of sampling probabilities after-the-fact. More times than not, however, information is irretrievably lost when this aspect of the sampling design is not explicitly planned.

The common procedure of pairing damaged areas with nearby undamaged areas does not provide the information needed for risk rating. Its deficiency lies in the fact that the relative sampling probabilities to be assigned plots in the damaged and undamaged areas cannot be determined without additional information. The additional information required to assign relative sampling probabilities is an es-

timate of the total area included in the damaged and in the undamaged subsets of the population within each cell of the experimental design. This ratio can usually be provided only by a further inventory of the total population. The results of this lack of relative sampling probabilities is that the a priori distributions needed for discriminant function analysis and conditional probability models are unknown. At most, paired plots can help to define the variables to be included in conditional probability models and perhaps lead to an ordinal scale of risk.

Analysis Methods

Let us consider first the model describing the probability of a pest outbreak. Typically, linear regression is used to describe the relationship between a dependent variable and a set of independent variables; however, the occurrence of a pest outbreak in a stand is a dichotomous event (i.e., it either occurs or fails to occur). From statistical literature (Neter and Maynes 1970, Walker and Duncan 1967, Hamilton 1974), we find that the logistic function is the preferred model for expressing the relationship between a dichotomous dependent variable and a set of independent variables. Thus, the logistic function has been selected as the basic functional form to be used in describing the relationship between probability of pest outbreak in a stand and the set of independent variables that describe the stand. The logistic function is expressed as

$$P = \frac{1}{1 + e^{-X'\beta}}$$

where

P = probability of occurrence of a pest outbreak,
X' = transpose of the vector of independent variables,
β = vector of nonlinear regression coefficients.

The first step in developing the probability of pest outbreak model is to identify the independent variables that are useful descriptors of the probability of pest outbreak. The logistic function is nonlinear in the parameters. Thus, the data-screening procedures associated with commonly used linear regression methods for selection of the appropriate independent variables are not applicable. Further, most nonlinear regression programs are not efficient procedures for screening alternative sets of independent variables, especially when data sets are large. We have found an algorithm described by Sterling and others (1969) to be useful for selecting subsets of variables. A PL/1 computer program that performs this screening is described by Hamilton and Wendt (1975). With this program, those subsets of independent variables can be identified that best estimate the probability of a pest outbreak in a stand. In addition, significant interaction effects are identified and appropriate transformations of independent variables are suggested.

The results of data-screening are combined with the modelers' understanding of the occurrence of the pest outbreak being modeled in order to determine which subsets of independent variables should be considered further. Once "optimal" subsets of independent variables have been identified, nonlinear regression is used to estimate β, the vector of nonlinear regression coefficients. A computer program designed to take advantage of the properties of the logistic function in order to efficiently estimate these regression coefficients is described by Hamilton (1974).

The contagious nature of many pest outbreaks has implications for both the sampling design and the analysis used to develop a risk-rating model. We have already discussed the impact on sampling designs of the need to collect spatial information. An example of including contagion in a risk-rating model is provided by Heller and others (1977). In consultation with them, we developed a two-stage procedure for analysis. The first stage of analysis consisted of the development of a logistic regression model to predict the probability of a Douglas-fir tussock moth outbreak on a sample location, ignoring the status of adjacent sample locations. The second stage of analysis consisted of the development of a second model that included an additional variable which described the status of adjacent sample locations. For the first year of an outbreak, this variable was defined as the average predicted probability of outbreak, estimated by the first stage model, for eight systematically arranged sample locations adjacent to the subject (central) sample location. Parameters of the second-stage model were estimated using the same data set that was used to estimate parameters of the first stage model. For subsequent years of a regional outbreak the variable, "average probability of outbreak for adjacent sample locations," was replaced by the variable "average defoliation in the previous year for adjacent sample locations."

Discriminant analysis is an alternative approach to the development of a risk-rating model. Logistic regression analysis and discriminant function analysis have been compared quite extensively in the statistical literature. Linear discriminant analysis assumes that the two

populations from which an observation may be drawn are multivariate normal populations with equal covariance matrices. Efron (1975) demonstrates that when the assumptions of discriminant analysis are met, logistic regression is typically only one-half to two-thirds as effective as discriminant analysis for classification. On the other hand, the ability to use an efficient sampling design with logistic regression may overcome the loss in analysis sensitivity.

Press and Wilson (1978) present several arguments against the general use of discriminant analysis. When the two populations do not follow a multivariate normal distribution with equal covariance matrices, the use of linear discriminant analysis may lead to very poor results. When the normality assumption is not met, linear discriminant function estimators of the slope coefficients of logistic regression will be consistent. For example, if one of the independent variables is a categorical variable then that variable is not normally distributed. Therefore, we cannot expect discriminant function coefficients, when used in the logistic model, to predict accurately the probability the observation is in a given class, even for very large sample sizes. Furthermore, maximum likelihood estimators of coefficients of the logistic regression model are functions of the sufficient statistics while discriminant function estimators are not. Both Efron (1975) and Press and Wilson (1978) suggest that for the non-normal case, maximum likelihood estimators of logistic regression are theoretically superior to discriminant function estimators.

O'Neill (1980) suggests that in certain cases, the maximum likelihood estimator of the optimal discriminant rule for the specific distributions encountered is preferable to logistic regression. This, however, is not an alternative analysis available to most individuals developing risk-rating systems.

An additional strength of a risk-rating system based on a model that estimates the probability of a pest outbreak for a given stand is that it may more closely describe our understanding of the biological processes involved in pest outbreaks. Rarely are we able to predict with certainty whether or not a given stand will experience a pest outbreak in a given time interval. Thus, for most management decisions, the information required is not a simple classification of a stand into a high-risk or a low-risk category. Instead, we require a statement of the probability of pest outbreak and an estimate of loss, assuming that the outbreak occurs. These two values permit the manager to estimate the expected value of loss under alternative management strategies. Further, when the manager is provided with these two values, he is free to define "high risk" in the context of the management decisions he must make. If the manager is completely familiar with discriminant function analysis, these same capabilities are available using discriminant function analysis by making use of the probabilities of misclassification. If the assumptions of multivariate normality are not satisfied, however, the use of maximum likelihood estimators for logistic regression appears to be preferable, especially when many of the independent variables are qualitative (Press and Wilson 1978).

PHASE II--ESTIMATING DAMAGE

Sampling Requirements

This phase of the analysis can be founded on data from sample locations selected with less rigor than was required in phase I. The population to be sampled is exclusively comprised of areas that were classified in phase I as "outbreak areas." Within this population, samples may be selected to complete an experimental design. The design matrix would specify sample numbers arrayed by the levels of factors considered to have major influence on the level of damage. Within the cells of this design matrix, sample locations should be selected at random.

Analysis Methods

In most applications of risk-rating models to management decisionmaking, the second model (describing loss given a pest outbreak has occurred) is as important as the model describing the probability of occurrence of the outbreak. As mentioned previously, the functional form of this model will depend on the nature of loss caused by a given pest outbreak. If loss is expressed as an increase in individual tree mortality, the second model will be a model describing the probability of mortality of individual trees, given the pest outbreak has occurred. The steps in developing such a model are similar to those just discussed for development of the probability of pest outbreak model.

If loss is expressed as a reduction in tree growth, the second model may be a set of models describing tree growth given the pest outbreak has occurred (Wickman 1979, Wickman et al. 1980). The functional form of such models will be determined by the components of tree growth that must be described.

When simulation models of insect population dynamics (Colbert 1978) are available, they can be used to estimate levels of damage in the context of phase II.

SUMMARY

In summary, development of a pest risk-rating system depends on two essential features. First, data must be collected with quantifiable sampling probabilities from both the infested and noninfested segments of the population. Second, the risk-rating system should consist of two basic components: (1) a model that estimates the probability of pest outbreak in a stand, and (2) a conditional model that estimates losses, assuming that a pest outbreak has occurred.

LITERATURE CITED

Colbert, J. J. 1978. Douglas-fir tussock moth population outbreak model. *In* Proc. Soc. Amer. Foresters Ann. Meeting. [St. Louis, Mo., Oct. 1978.] p. 253-255.

Daniels, R. F., W. A. Leuschner, S. J. Zarnoch, H. E. Burkhart, and R. R. Hicks. 1979. A method for estimating the probability of southern pine beetle outbreaks. For. Sci. 25(2):265-269.

Efron, B. 1975. The efficiency of logistic regression compared to normal discriminant analysis. J. Am. Stat. Assoc. 70(352):892-898.

Hamilton, D. A., Jr. 1974. Event probabilities estimated by regression. U.S. Dep. Agric. For. Serv., Res. Pap. INT-152, 18 p. Intermountain For. Range Exp. Stn., Ogden, Utah.

Hamilton, D. A., Jr., and D.L.R. Wendt. 1975. SCREEN: a computer program to identify predictors of dichotomous dependent variables. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. INT-22, 20 p. Intermountain For. Range Exp. Stn., Ogden, Utah.

Heller, R. C., and W. A. Miller. 1976. Identification of preferred Douglas-fir tussock moth sites by photo interpretation of stand, site, and defoliation conditions. Final report to the USDA Douglas-fir Tussock Moth Program. 24 p. Univ. of Idaho, Moscow.

Heller, R. C., S. A. Sader, and W. A. Miller. 1977. Identification of preferred Douglas-fir tussock moth sites by photo interpretation of stand, site, and defoliation conditions. Final report to the USDA Douglas-fir Tussock Moth Program. 23 p. Univ. of Idaho, Moscow.

Lorio, P. L., Jr. 1978. Developing stand risk classes for the southern pine beetle. U.S. Dep. Agric. For. Serv., Res. Pap. SO-144, 9 p. South. For. Exp. Stn., New Orleans, La.

Neter, J., and E. S. Maynes. 1970. On the appropriateness of the correlation coefficients with a 0,1 dependent variable. J. Am. Stat. Assoc. 65(330):501-509.

O'Neill, T. J. 1980. The general distribution of the error rate of a classification procedure with application to logistic regression discrimination. J. Am. Stat. Assoc. 75(369):154-160.

Press, S. J., and S. Wilson. 1978. Choosing between logistic regression and discriminant analysis. J. Am. Stat. Assoc. 73(364):699-705.

Stage, A. R. 1974. Playing with probabilities: one key to meeting information objectives. p. 1837. *In* Inventory design and analysis. Proc. of a workshop. Inventory Working Group, Soc. of Am. For., July 23-25, 1974. W. E. Frayer, G. B. Hartmen, and D. B. Bower, eds. Colo. State Univ., Fort Collins.

Stage, A. R. 1975. Forest stand prognosis in the presence of pests: developing the expectations. p. 233-245. *In* Management of lodgepole pine ecosystems: symposium proceedings. D. M. Baumgartner, ed. Wash. State Univ., Pullman.

Sterling, T. D., R. G. Binks, S. Haberman, and S. V. Pollack. 1969. Robot data screening--a ubiquitous automatic search technique. *In* Statistical computation. p. 319-333. R. C. Milton and J. A. Nelder, eds. New York: Academic Press. 462 p.

Talerico, R. L., C. M. Newton, and H. T. Valentine. 1978. Pest control decisions by decision-tree analysis. J. For. 76(1):16-19.

Walker, S. H., and D. B. Duncan. 1967. Estimation of the probability of an event as a function of several independent variables. Biometrika 54: 167-179.

Wickman, B. E. 1978. Tree mortality and top-kill related to defoliation by the Douglas-fir tussock moth in the Blue Mountains outbreak. U.S. Dep. Agric. For. Serv., Res. Pap. PNW-233, 47 p. Pacific Northwest For. Range Exp. Stn., Portland, Ore.

RISK-RATING RED PINE PLANTATIONS TO PREDICT LOSSES FROM SARATOGA SPITTLEBUG FOR MANAGEMENT DECISIONS

Robert L. Heyd and Louis F. Wilson[1]

The risk-rating system presented is currently used by the Michigan Department of Natural Resources to evaluate all proposed red pine planting sites and plantations less than 10 years old for Saratoga spittlebug damage. We quantify potential losses with this system and then provide forest land managers with management strategies based on sound economics. This service has increased the utility of the forest pest management program and boosted many persons' interest in and opinion of the program.

THE PROBLEM

The Saratoga spittlebug occurs wherever red pine grows in eastern North America. It injures plantation red pine between 2 and 15 ft tall. Young plantations have failed from its damage. Severely injured plantations may survive but produce low-grade products.

More specifically, adult Saratoga spittlebug feeding causes tree deformities such as lower-bole limbiness, large knots, crook and sweep, and loss of wood volume from growth loss and/or tree mortality. Crooked pulp sticks increase loading and hauling costs. In addition, by the time crook and sweep are visible, much growth loss has already occurred. Injury often occurs in pockets within a planting, and pocket openings produce limby perimeter trees. Increased limbiness may cull perimeter trees for use as utility poles and pilings because both have limitations on the number and size of knots.

RECOGNIZING THE SARATOGA SPITTLEBUG AND ITS INJURY

The spittlebug overwinters in the egg stage. Eggs are laid under the outer scales of large buds in the upper branches of red pine in mid- to late summer. Usually, the female lays several eggs in each bud. They cause a noticeable irregularity on the outer surface of the bud scales.

Hatching is usually complete by mid-May, and the young nymphs drop or are blown to the ground. They then crawl to alternate host plants on the plantation floor (e.g., sweet-fern) and begin feeding. As they feed they form the characteristic spittlemass. They pass through five instars; and after 7 to 10 weeks, when fully developed, they leave the spittlemass, climb to the upper parts of their host plants, and transform to adults.

The adults then fly to the pine hosts and feed on the needle-bearing twigs. The spittlebug's feeding period is from late June to the end of September, but its peak activity occurs between mid-July and mid-August. The adult can be identified by the white arrow-shaped mark on the head and thorax.

The first easily recognized symptom of adult spittlebug injury on red pine is one or more reddish-brown (flagged) branches. One can tell that spittlebug has caused this by scraping away the bark and looking for tan or brown flecks on the surface of the wood and inner bark. These puncture wounds or scars develop at the location of adult feeding and restrict nutrient and water transport in the branches. Light scarring causes reduced branch vigor and growth loss. When puncture wounds or scars are numerous, the branches die and cause the characteristic flagging.

NYMPHAL HOSTS

The Saratoga spittlebug nymph feeds on several woody and herbaceous ground cover plants of the forest floor. Only the adult feeds on pine. Important nymphal hosts are sweet-fern (*Comptonia peregrina* [L.] Coult.), willow (*Salix* spp.), bramble (*Rubus* spp.), orange hawkweek (*Hieracium aurantiacum* L.), low blueberry (*Vaccinium vacillans* Torr.), sour-top blueberry (*Vaccinium myrtilloides* Michx.), goldenrod (*Solidago* spp.), sheep-sorrel (*Rumex acetosella* L.), old-field cinquefoil (*Potentilla simplex* Michx.), spotted knapweek (*Centaurea maculosa* Lam.), everlasting (*Antennaria neglecta* Greene), meadow-sweet (*Spiraea alba* Du Roi), wild lettuce (*Lactuca canadensis*), and prairie ragwort (*Senecio plattensis*).

Sweet-fern, which heads the list, is the most important host. Heavy spittlebug infestations are often related to the

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amount of sweet-fern in a plantation. Nonhost plants are grasses, sedges, lichens, mosses, and club-mosses.

APPROACHING THE PROBLEM

Figure 1 presents the steps involved in assessing the influence of the Saratoga spittlebug on the management of proposed red pine planting sites or established plantations.

RISK-RATING

Prospective red pine sites should be risk-rated for potential spittlebug injury before planting. Established plantations also can be risk-rated. There are three risk categories: low, moderate, and high. Low risk means that injury from spittlebugs will not occur or at most will be negligible. Moderate risk indicates that spittlebugs may cause some growth loss, light flagging injury on scattered branch tips, and crooked stems in a few trees. High risk indicates potentially heavy growth loss, many crooked stems, and numerous top-killed or dead trees.

Saratoga spittlebugs cause economic damage only when suitable alternate hosts are abundant. Thus, we consider the kinds and density of alternate hosts when selecting planting sites or when determining the risk of injury to young red pine stands. Of the numerous alternate hosts, sweet-fern is the most important: heavy infestations are usually correlated with the density of sweet-fern. A prospective planting site or plantation is risk-rated

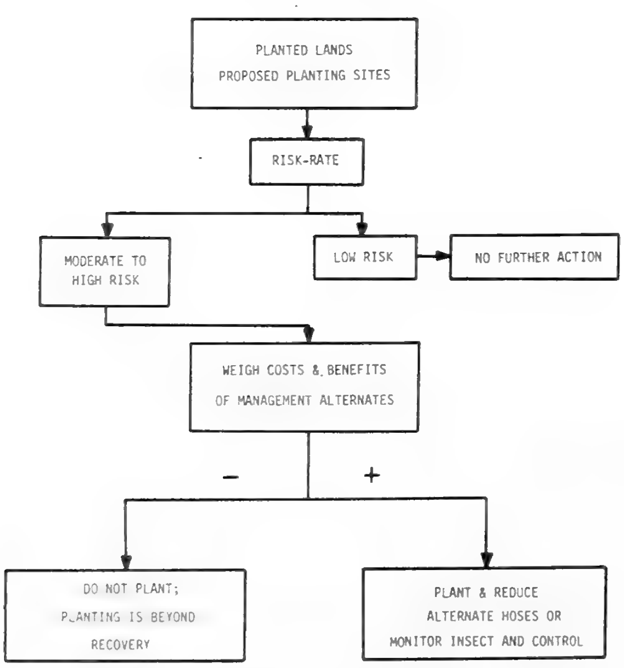

Figure 1.--Flowchart of steps in determining management strategies for red pine, based on potential susceptibility to damage by Saratoga spittlebug.

by estimating the amount of sweet-fern relative to the amounts of other ground cover plants.

Risk-rating should be conducted between May and September so that alternative hosts can be easily identified. However, the procedure should be done by mid-June in young plantings in the event control measures are needed that year.

Well-stocked stands of red pine more than 15 ft tall and not yet showing visible symptoms of spittlebug injury are safe and need not be risk-rated. Trees over 20 ft tall are usually safe at any stocking density.

The equipment needed for ground survey includes a large-scale sketch or map of planting, a clipboard and pencil, and a risk-rating form.

Ground Survey Procedures

1. Draw transect lines on planting sketch or map. Make transects parallel and spaced 2 to 5 chains apart. In unplanted land with good visibility, use a 5-chain spacing; as lateral view is inhibited by trees and/or terrain, use a spacing as close as 2 chains.

2. Walk transects. Stop every 2 chains to observe the ground cover. First, estimate percent of ground cover occupied by sweet-fern, and then the percent occupied by nonhosts (e.g., grasses, sedges, lichens, mosses) and bare ground. Then estimate percent of the other host plants or determine it by subtracting the percent sweet-fern and percent nonhosts from 100 percent.

3. Use risk-rating triangle (fig. 2) to determine if risk is low, moderate, or high at each stop. Place a small *l*, *m*, or *h* at each stop to indicate low, moderate, or high risk, respectively. *Note:* While walking transects, observe and document any changes in overall ground cover. Having this in writing will help you draw boundaries between areas of different risk.

4. After completing all observations, draw boundaries on the sketch or map of area, enclosing areas of similar risk (fig. 3).

5. Determine the acreage in each risk category.

6. See section on Management Strategies to formulate plan of action, if moderate- or high-risk areas are present.

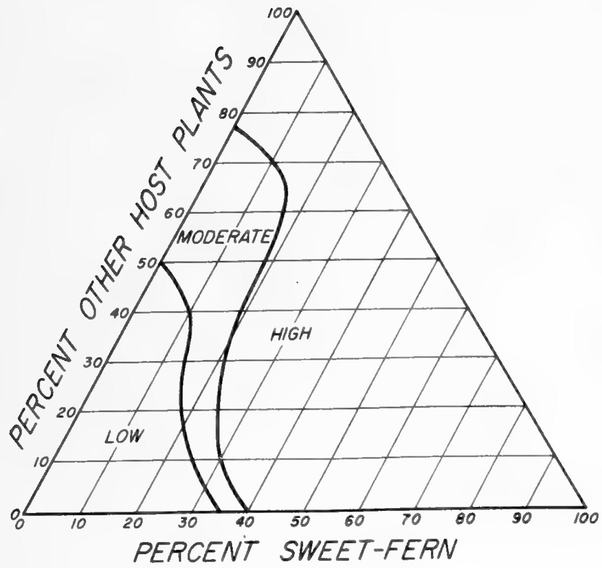

Figure 2.--This risk-rating triangle plots the hazard for Saratoga spittlebug infestation as a function of the kind and density of alternate host plants as ground cover.

At times it will be difficult to distinguish low from moderate risk and moderate from high risk. When this situation prevails, there are two rules of thumb:

1. If this is unplanted land or if trees are shorter than 8 ft tall, favor the greater risk. Otherwise, favor the lesser risk.

2. If bare ground, moss, and/or lichens comprise greater than 25 percent of the ground cover canopy, favor the lesser risk.

Helicopter Survey

A helicopter survey is useful for risk-rating a large number of established plantations or proposed planting areas. Low-risk areas can be distinguished from moderate- and high-risk areas, and an excellent view of the size and distribution of different risk areas within each plantation is possible.

HOW TO SELECT A MANAGEMENT STRATEGY

After risk-rating an unplanted area or plantation, one decides whether further examination is needed. If the risk is low, the potential damage is also low and further evaluation is unnecessary. If risk is moderate or high, however, further evaluations, decisions, and actions are warranted.

Unplanted Sites

On unplanted land risk-rated moderate or high, one has the options to (1) plant and accept the risk, (2) plant and monitor the insect and control any threatening populations, (3) reduce the alternate hosts for long-term control of the spittlebug and then plant, or (4) not plant. The selected strategy should be economically sound. The costs of each strategy should be carefully weighed against the benefits, and a strategy providing an acceptable return on investments should then be selected.

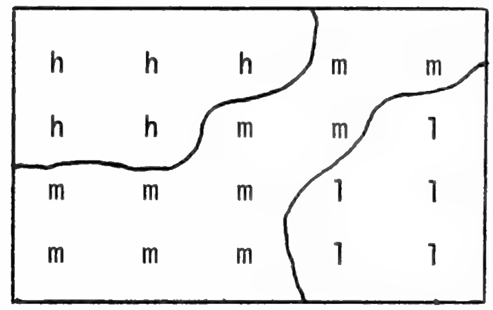

Figure 3.--A sample plot sketch pinpointing areas of low, moderate, and high risk for Saratoga spittlebug attacks.

More specifically, the present value of returns (PVR) is compared to the present value of costs (PVC) to derive the net present value (NPV) of a particular management strategy (NPV = PVR-PVC). This calculation is done by discounting projected costs and returns at the desired rate over the period in which each cost or return is to be realized. If the resulting net present value is greater than or equal to zero, (PVR ≧ PVC), the management strategy in question produces or exceeds the desired return on dollars invested. In addition, the size of the positive net present value means that additional dollars can be spent now and still achieve the given return. A negative net present value means the management strategy does not provide the desired return on investment. Again, the size of the net present value represents the dollar amount in present money (money which can be spent now) that a project either falls short (-NPV) or exceeds (+NPV) the desired return on investment.

Here is an example using net present value to select the best management strategy. Let's assume we want to plant an area to red pine, and this acreage has significant portions in the moderate and high Saratoga spittlebug risk categories.

We want to plant 600 trees per acre to be harvested at age 45 as pulpwood. For the purpose of this example, we set establishment cost at $116.72 per acre (the cost of hand planting[2]). Any additional costs and returns expected will depend on the management strategy selected. Table 1 presents the net present values resulting from different management strategies for site indexes 50, 60, and 70. The yields were calculated using a computer model of red pine yields.[3] The yield in cords of each management strategy was used to determine stumpage prices.[4]

The upper and lower limits of growth loss in a moderate-risk area are 4 and 10 years, respectively. Growth loss caused by the Saratoga spittlebug more or less uniformly affects the productivity of the entire tree, so one sees a reduction in height and diameter growth. Thus, reduced yields from growth loss were calculated by using the volume yields of a rotation shortened by the years of lost growth. For example, given 4 years' growth loss, the yield of this planting would be calculated for age 41 years instead of 45 years. Stumpage price was not changed to reflect difference in handling, loading, and hauling costs resulting from increased limbiness, crook, or sweep.

Examining table 1, we see that it is apparent that accepting the risk of injury is not an option for high-risk areas or for moderate-risk areas of site index 50 or less at the selected rates.

Monitoring and spraying produces the highest return consistently. Reducing alternate hosts is a much more expensive operation, yet it provides greater NPV's than accepting the risk in most instances. The only exceptions to this are for rates 8 to 9 percent in moderate risk-lower limits on site index 70. However, any increase in productivity of the site from reducing ground cover competition was not considered because of a lack of yield data for site indexes greater than 70. The net present values for site indexes 50 and 60 do include an increase in yield reflecting a release from ground cover competition. This is shown most dramatically in the high-risk areas with site indexes of 50 and 60. Here, reducing alternate hosts yields higher NPV's than monitoring and spraying.

Plantations

Basically, the same procedure for making management decisions for proposed planting sites is used in established plantations. The present value of returns is calculated by discounting the value of the crop at maturity by the number of years to maturity at the desired interest rate. The present value of returns (PVR) is then compared to the present value of costs (PVC) for each management strategy (and any other costs to be incurred) to calculate net present value (NPV). If the trees are already injured (i.e., showing growth loss, deformity, or mortality), the value of the crop at maturity is modified by then accounting for reduced yield from growth loss and/or tree mortality and/or deformities that may alter the value of the crop.

If monitoring and control is chosen as the best management strategy, a nymphal survey (referred to as monitoring) is scheduled for the third year of the plantation. In older plantations, the survey should be made that year. Control of the adult spittlebug is then recommended on the basis of this survey.

SARATOGA SPITTLEBUG MANAGEMENT

The Saratoga spittlebug can be managed by preventive, cultural, and chemical measures. Prevention involves restricting the planting of spittlebug-susceptible pines to only the no-risk or low-risk areas. This may mean not planting an entire area or omitting just a few small islands or pockets where the important alternate hosts predominate. Not planting a small portion of an area may greatly enhance esthetic and/or wildlife values in some regions. Pockets with 35 percent or more of the ground cover in sweet-fern are especially troublesome. If they are planted and then infested, without control measures, heavy injury is almost inevitable. Even if heavy spittlebug injury does not occur, such areas usually produce slow-growing trees until after crown closure due to direct competition with sweet-fern.

Cultural control implies reduction of the principal alternate hosts--especially sweet-fern. Deep plowing disrupts and buries sweet-fern and usually curtails rapid regeneration. However, this procedure disrupts soil structure and water-

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[2] Cost of hand planting = $43.82 + (41.298 + .051 × trees/acre) taken from Olson, Lundgren, and Rose (1978).

[3] Red pine yield computer model developed by A. L. Lundgren, Principal Economist, USDA Forest Service, St. Paul, Minnesota.

[4] Stumpage price/acre = 6.44 + (.36 × cords harvested). Equation developed by Jeffrey T. Olson, Economist, Michigan Dept. of Natural Resources.

Table 1.--Net present values per acre for different management strategies and site indexes for planting sites with moderate and high Saratoga spittlebug risk. The proposed planting is 600 red pine per acre to be harvested at age 45.

STRATEGY	MODERATE RISK: Net present values at rate (%) 7	8	9	10	HIGH RISK: Net present values at rate (%) 7	8	9	10
SITE INDEX 70								
Accept risk (lower limit)[1]	246	122	41	-12	--	--	--	--
Accept risk (upper limit)[2]	216	83	3	-44	-117	-117	-117	-117
Reduce alternate hosts[3]	265	114	15	-49	265	114	15	-49
Monitor and spray[4]	314	164	66	1	307	157	59	-5
No risk[5]	325	174	75	11	325	174	75	11
SITE INDEX 60								
Accept risk (lower limit)	89	19	-27	-58	--	--	--	--
Accept risk (upper limit)	81	2	-45	-73	-117	-117	-117	-117
Reduce alternate hosts	132	27	-42	-88	178	57	-23	-74
Monitor and spray	136	46	-12	-50	128	39	-19	-57
No risk	146	56	-2	-41	146	56	-2	-41
SITE INDEX 50								
Monitor and spray	14	-35	-67	-88	7	-42	-73	-93
No risk	31	-19	-52	-74	31	-19	-53	-74

[1] Moderate risk = 4 years' lost growth

[2] Moderate risk = 10 years' lost growth. However, yield at 45 years was discounted to age 55 because loss of 10 years' growth at age 45 reduced yield below acceptable limits; HIGH RISK = Total loss.

[3] Cost = $60/acre. Reducing alternate hosts increased site index by 5 for moderate-risk areas and 10 for high-risk areas for site indexes 50 and 60. No data for yields on site indexes greater than 70 were available.

[4] Spray cost = $12/acre for aerial application. Moderate-risk areas were evaluated three times and sprayed once. High-risk areas had three evaluations and two sprays. If site index is less than or equal to 50, add one evaluation and one spray to account for increased length of spittlebug-susceptible height stage (3 to 15 ft) due to slow growth.

[5] Yield expected with no threat of loss or need to control presented for comparison.

holding capacity of the plowed soil layer. This side effect may be critical in sandy soils. Shallow plowing or mowing stimulates growth of sweet-fern and should be avoided unless repeated for 2 to 3 years--the cost of which may be prohibitive. Chemical herbicides do not disturb the soil and provide what appears to be the most reasonable method of reducing ground vegetation. When applied properly, herbicides suppress sweet-fern, brambles, and certain alternate hosts. These agents seem to provide long-term suppression, which will benefit future crops.

Registered pesticides may be used effectively against the adult spittlebug. Pesticide application must be timed precisely between adult emergence and egg laying (usually early July). In high-risk areas, two or three applications may be needed before the trees outgrow the risk. Spray operations are recommended on the basis of the insect evaluation survey--not on damage symptoms. Damage symptoms are a result of the previous year's injury, and spittlebug populations may have since collapsed.

ACKNOWLEDGMENTS

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LITERATURE CITED

Olson, J. T., A. L. Lundgren, and D. Rose. 1978. Equations for estimating stand establishment, release, and thinning cost in the Lake States. U.S. Dep. Agric. For. Serv., Res. Pap. NC-163. North Central For. Exp. Stn., St. Paul, Minnesota.

HAZARD-RATING LODGEPOLE PINE FOR SUSCEPTIBILITY TO MOUNTAIN PINE BEETLE INFESTATION

Mark D. McGregor, Gene D. Amman, and Walter E. Cole[1]

Abstract.--In 1975, Montana stands of lodgepole pine, *Pinus contorta* var. *latifolia* Engelmann, were rated using Amman's system for risk of infestation by mountain pine beetle, *Dendroctonus ponderosae* Hopkins. Hazard rating was based on three factors--climate suitability of the stand, average d.b.h., and average tree age. The system helped direct land managers to susceptible stands where harvest of trees is reducing losses to the beetles. During the 5 years following rating, 11 percent of the high-hazard stands became infested; only 1 percent of the stands rated moderate became infested; and less than 1 percent of the stands rated light became infested.

INTRODUCTION

Forests of lodgepole pine (*Pinus contorta* Douglas var. *latifolia* Engelmann) provide important cover on more than 13 million acres (5.2 million ha) in 11 Western States (Wellner 1975) and over 49.5 million acres (19.8 million ha) in western Canada (McDougal 1975). This forest cover serves many purposes, such as scenic backdrops for recreational areas, protection for watersheds, habitat for game animals, areas for domestic livestock grazing, and raw materials for lumber, poles, posts, and pulp (Tackle 1954). Lodgepole pine has a wide geographic range, extending from Alaska south to northern Baja, California, and east through Wyoming and Colorado. It can be found from sea level in Alaska to 11,500 ft (3,485 m) in Colorado, although it grows best where the annual precipitation is 21 inches (52.5 cm) or more (Mason 1915).

Prior to World War II, lodgepole pine was considered a weed species and of little value (Wellner 1978). Since that time, commercial importance has increased considerably in Montana, Idaho, Wyoming, and Colorado--the States with over 80 percent of the lodgepole pine in this country --and also in Utah and Oregon (Wikstrom 1957).

With lodgepole's increasing importance, managers have become more conscientious about its protection and perpetuation. Without protection and management, lodgepole pine forests are transient pioneers giving way to natural factors such as insects, diseases, and in the absence of wildfire, to succeeding vegetation (Roe and Amman 1970).

Infestations of the mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopk.) are probably the most important natural factor affecting lodgepole pine. This pest makes it very difficult to convert unmanaged to regulated forests with even-flow, sustained yield (Wellner 1978). During the past few decades, the beetle, rather than the manager, has set priorities and cutting schedules.

The MPB is indigenous to North America and probably has been active in lodgepole pine ecosystems almost as long as the tree has existed. Endemic beetle populations infest windthrown lodgepole pine with roots still intact; lodgepole pine affected by root pathogens, dwarf mistletoe, rust fungi, defoliators, drought, porcupines; and trees partially infested with secondary bark beetles. Once the stand attains conditions conducive to beetles (i.e., large-diameter trees and thick phloem), an epidemic begins. Attacks are concentrated on open-grown, large-diameter trees ≧ 80 years old, with thick phloem, in habitat types and at elevations suitable for both good lodgepole pine growth and beetle survival.

MPB infestations in a given area generally occur about every 20 to 40 years, depending on how rapidly stands of trees grow to large diameters containing thick phloem and have other conditions favorable for beetle development (Amman 1977). For example, the southern end of the Targhee National Forest in southeastern Idaho was subjected to an epidemic infestation of MPB in the late 1950's and early 1960's. After most of the large-diameter lodgepole pine were killed, the beetle population subsided. Now, some 20 years after the beginning of the previous infestation, another epidemic has started.

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HAZARD-RATING SYSTEMS

Systems for rating the risk of MPB outbreaks in lodgepole pine forests usually have been based on (1) historical evaluation of the frequency and intensity of infestations within a region; (2) correlation of damage intensity and habitat type; (3) evaluation of damage by climatic zones; (4) host tree characteristics, including diameter and phloem thickness; (5) stand characteristics, including crown competition, periodic growth rate, and basal area; and (6) various combinations of these factors.

A map of relative stand hazard from MPB has been developed for the central and northern Rockies, based on the frequency and intensity of past infestations (Crookston et al. 1977). The map is useful in drawing attention to stands in areas that have suffered repeated severe outbreaks, so that these stands can be rated using specific hazard-rating systems.

Beetle-caused tree mortality has been related to habitat types (Roe and Amman 1970). The risk of growing trees to a specific diameter was considered the product of the proportion of trees killed in a diameter class times the proportion of stands on a given habitat type that showed evidence of prior infestation. For example, growing trees to 16 inches (40.6 cm) d.b.h. would be a high hazard (75 percent probability of loss) on *Abies lasiocarpa/Pachistima myrsinites* type, where 82 percent of the trees were killed and 92 percent of the stands were infested. In contrast, the hazard of growing 16-inch d.b.h. trees on the *Abies lasiocarpa/Vaccinium scoparium* type would be much less, with about two-thirds of the trees expected to survive (36 percent probability of loss). However, because of the elevation range in some habitat types and corresponding range in MPB-caused mortality (McGregor 1978), elevation must also be considered in hazard rating. Where management plans are being developed in Region 1, habitat type and elevation are included in stand hazard rating.

Safranyik et al. (1974) used weather data to define hazard by climatic regions in British Columbia. Where climatic conditions were highly conducive to outbreaks, stand susceptibility was further evaluated using age and tree diameter. Although similar maps have not been developed for the central and northern Rocky Mountains, the effects of climatic conditions throughout the region were taken into account with the system developed by Amman et al. (1977).

Tree diameter and phloem thickness were used in a hazard-rating system to assess beetle population potential within three infested areas in Colorado (Cole 1978, Cole and Cahill 1976). Observations in these stands suggest that where 20 percent of the trees ≧ 8 inches (10 cm) d.b.h. in a stand have a phloem ≧ 0.11 inch (2.79 mm) thick, the stand has the potential for significant MPB outbreaks and should be considered for harvesting.

Mahoney (1978) mentions the investigations of Schenk et al., who used stand characteristics, crown competition factor (CCF), and percent of basal area in lodgepole pine (LPPBA) for a stand hazard rating (SHR) system in western Montana and northwestern Idaho. The formula is

$$SHR = CCF \times \frac{\%\ LPPBA}{100}$$

Schenk's team reported good agreement between the stand hazard rating and lodgepole pine mortality in stands they measured. Mortality increased with increased crown competition and BA in lodgepole pine. However, this relation did not hold when the rating system was used for lodgepole pine in Montana, southeastern Idaho, and northwestern Wyoming (McGregor 1978), where infestations have been more intense in open rather than dense stands. Data from stands in Montana show that as crown competition increases, lodgepole pine mortality decreases (fig. 1).

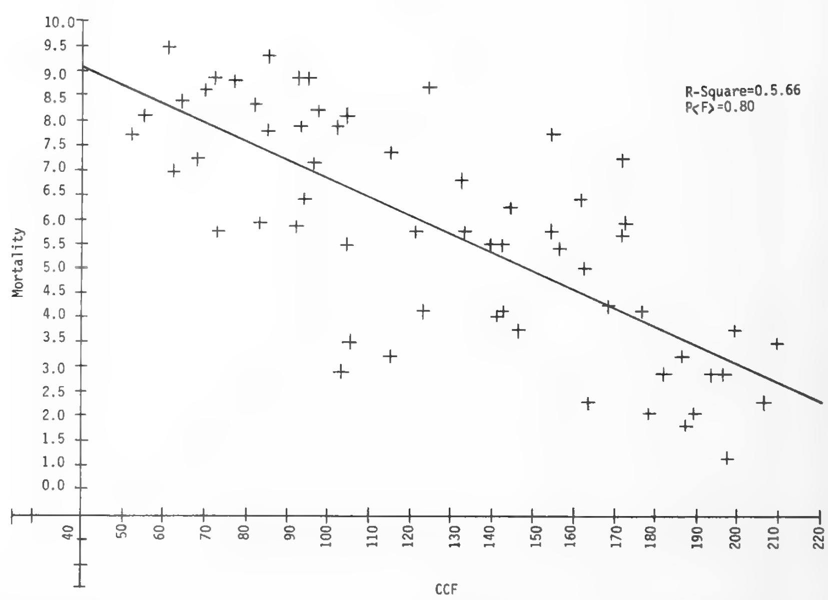

Figure 1.--The relationship of lodgepole pine to CCF for 62 stands in Montana, 1978-79. Note: Data transformed,

$Y' = \sqrt{Y + 3/8}$

Periodic growth ratios (PGR) also have been suggested as a means of evaluating stand susceptibility to MPB (Mahoney 1978). The formula is

$$PGR = \frac{\text{Current 5-year radial increment}}{\text{Previous 5-year radial increment}}$$

PGR is considered a measure of current trend in stand vigor. Values > 1.0 indicate rising growth and vigor and < 1.0 indicate a decline in vigor. A PGR value of < 0.9 is considered a decline in vigor that indicates a lodgepole pine stand which will support an increasing MPB population and sustain an epidemic (Mahoney 1978).

Mahoney found good agreement for PGR and beetle activity in 21 stands in northern Idaho and western Montana. However, PGR does not distinguish among fast- and slow-growing trees. For example, suppressed and dominant trees can have the same PGR, but the dominant group obviously is in much better health and will have thicker phloem. Mahoney (1978) stated, "Lodgepole pine stands that are growing relatively well, but suffer a decline in growth rate, should provide trees with thick phloem, but lowered resistance due to decline in PGR." However, we feel a decline in PGR is not necessary since we have observed infestations to start following an increase in tree growth sustained over a long period of time (Amman 1978).

AMMAN'S HAZARD-RATING SYSTEM

Amman's hazard-rating system (1977) for MPB in lodgepole pine is based on three factors: (1) climatic suitability (elevation and latitude of the stand for outbreak development, (2) average stand age, and (3) average stand d.b.h.

The rationale behind using these factors is as follows. Beetle populations do well at low elevations where temperatures are optimum for development. Development of the beetles slows as elevation increases, until at high elevations 2 years may be required to complete a generation (Amman 1973). If development is delayed, beetles may overwinter in life stages vulnerable to the harsh climate. In addition, beetles in a 2-year cycle are subjected to mortality factors for twice as long as those in a 1-year cycle. These adverse effects on the beetle population are reflected in reduced tree mortality at high elevations.

Climatic suitability is based on lodgepole pine losses to MPB observed at many different elevations and latitudes from Colorado to the Canadian border (fig. 2).

These data were plotted by elevation and latitude and separated into three loss classes--low risk when 25 percent or fewer lodgepole pine of commercial size (8.5 inches [22 cm] and larger d.b.h.) were lost; moderate risk when 25 to 50 percent of the commercial lodgepole were killed; and high risk when more than 50 percent of the commercial lodgepole were killed.

Average age of the stand enters into the picture, not as a measure of tree vigor, but rather of phloem suitability. Young trees, usually those less than 60 years of age, have phloem more spongy and resinous than older trees. Young trees tend to dry excessively after being infested and killed by the beetles. These characteristics are less apparent in trees between 60 and 80 years old. Trees over 80 tend to have phloem that is considerably firmer and contains fewer and smaller cortical resin ducts. Such trees generally dry slower than young trees, thus providing adequate moisture throughout beetle development.

Average d.b.h. is used because of the beetle's strong preference for large-diameter trees. These trees generally have thicker phloem and dry slower than small-diameter trees. MPB brood production is strongly influenced by phloem thickness and moisture in the tree (Cole et al. 1976).

Average d.b.h. of < 7 inches (18 cm) presents a low hazard; between 7 and 8 inches (18 to 20 cm), a moderate hazard; and > 8 inches (20 cm), a high hazard. Of these categories, only stands averaging ≥ 8 inches d.b.h. can be expected to have a sufficient number of large-diameter trees for the MPB population to build up and be sustained. The first two hazard

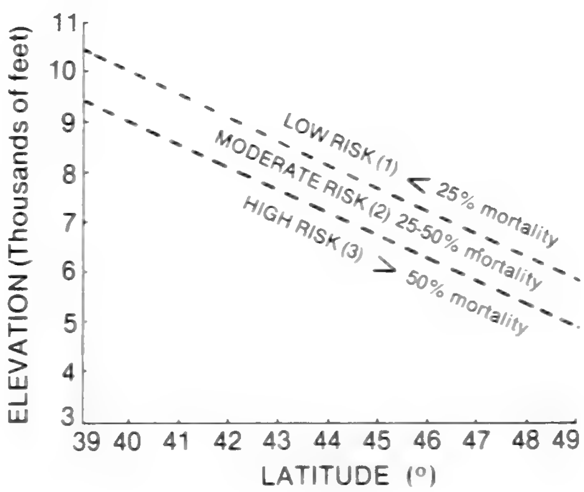

Figure 2.--Risk of mountain pine beetle infestation in lodgepole pine can be defined by zones of elevation and latitude. Percent mortality is for trees 8.5 inches (22 cm) d.b.h. and larger (Amman et al. 1977).

categories have fewer large trees, resulting in lower beetle populations and hence reduced tree losses.

Average elevation, stand age, and d.b.h. are obtained during a standard forest cruise. For small stands of under 20 acres (8.1 ha), a systematic random sample of 10 variable plots (10 BAF) is used. For larger stands, 20 variable plots are used. Field crews determined tree age by taking an increment core at breast height from the three trees closest to plot center that are 5 inches (13 cm) d.b.h. or larger. Average diameter is calculated from the diameters of all "in" lodgepole pine trees ≧ 5 inches (13 cm) in d.b.h.

Risk values have been assigned to each of three factors--climatic suitability, average tree age, and d.b.h. (table 1). This system has been valuable for stands hazard-rated on the Gallatin and Kootenai National Forests in Montana.

APPLICATION OF AMMAN'S SYSTEM

In 1975, 3 years after the start of an MPB epidemic, lodgepole pine stands on the Yaak Ranger District, Kootenai NF, were hazard rated for infestation potential. Hamel and McGregor (1976) based the rating on average age of lodgepole pine, average tree diameter, and elevation and latitude. Inventory data collected during 1977 and 1978 were used to update the original hazard classification and to produce a hazard map for the Kootenai NF in 1978. Calculations of susceptible areas showed 278,782 acres (112,867 ha) of high hazard; 56,656 acres (22,937 ha) of moderate hazard; and 93,699 acres (37,934 ha) low hazard. Table 2 shows infestations by year, in areas rated high, moderate, and low hazard.

In 1975, 5,110 of the 278,782 acres classed high-hazard were infested; no moderate- or low-hazard type was infested. By 1979, 29,413 acres (11 percent) of the high-hazard type, 455 acres (1 percent) of moderate hazard, and 26 acres (< 1 percent) of low hazard were infested. Lodgepole pine classed moderate and low hazard did not become infested until 1977, 5 years after the epidemic started.

Following rating, NF personnel assigned harvest priorities to high-hazard stands with a significant number of lodgepole pine ≧ 60 years old.[2] Table 3 gives the volume of lodgepole pine removed from these stands since 1976. Management for each stand includes salvage logging of infested trees and cutting the susceptible stands prior to beetle infestation.

We feel that implementing hazard-rating surveys and subsequent harvesting of the susceptible lodgepole pine stands have helped slow the infestation on the Kootenai NF. As a result, fewer acres have been infested and fewer trees have been killed (McGregor 1978).

USING HAZARD RATING IN FOREST SYSTEMS

When systems of hazard rating were being developed, it was expected that Forest Pest Management units would be responsible for them. Amman's system did require coordination between FPM groups from Regions 1, 2, and 4 with the Bark Beetle Research Group at the Intermountain Forest and Range Experiment Station, Ogden, Utah, in pooling of field data for development and validation of the system.

When the system was first used in Region 1, FPM worked with two National Forests to hazard rate lodgepole pine type with the old timber type maps, which were only 60 percent accurate at best. As new data became available from Stage I and Timber Inventory Surveys, and compartments, subcompartments, and stand maps were developed, there was a basis for updating the old timber type maps and for hazard rating individual lodgepole pine stands.

[2] Personal communication, John R. Naumann, Silviculturist, Kootenai National Forest, 1976.

Table 1.--Factors for rating lodgepole pine for the risk of mountain pine beetle infestation in Montana. By multiplying the following risk factors (1 = low; 2 = moderate, 3 = high) for elevation and latitude, average age, and average d.b.h., the stand's susceptibility classification is obtained; low = 1 to 6; moderate = 8 to 18; high = 27.

	RISK CLASSIFICATION		
	Low = 1	Moderate = 2	High = 3
Elevation-latitude	High	Moderate	Low
Average age (years)	<60	60-80	>80
Average d.b.h. (inches)	< 7	7-8	> 8

Table 2.--Mountain pine beetle infestation on the Kootenai National Forest, 1975-79

Hazard class	1975		1976		1977		1978		1979	
	Acres	Percent infested	Acres	Percent infested	Acres	Percent infested	Acres	Percent infested	Acres	Percent infested
High	5,110	2	17,638	6	10,863	4	20,562	7	29,413	11
Moderate	0	0	0	0	827	1	495	1	455	1
Low	0	0	0	0	10	<1	615	1	26	<1

Table 3.--Volumes of lodgepole pine removed from stands hazard rated on the Kootenai National Forest, 1976-80.

Year	Acres harvested	Fbm removed
1976	3,585	28,000
1977	1,600	21,000
1978	1,495	17,000
1979	5,400	463,000
1980[1]	8,400	72,000

[1] Figures for 1980 represent harvest for the period 1979 through fall of 1980. Fiscal year 1980 harvest is estimated at 8,400 acres containing 72,000 fbm of lodgepole pine (Jerrold Park, Silviculturist, Kootenai NF, 1980, personal communication).

Status of Hazard Rating in Region 1

All lodgepole pine type on National Forests in Montana has now been hazard rated by Amman's system. As Unit and District plans are developed and integrated into the overall Forest Management Plan, rating is being done on a stand-by-stand basis.

During the past 2 years, FPM in Region 1 has cooperated with forest inventory crews in collecting stand data that will provide the necessary information for hazard rating individual stands. Raw field data sent to the FPM office are card punched by Computer Science and analyzed in a program developed by statisticians in FPM. This program provides a hazard rating for each surveyed stand. The land manager then receives a listing of stands with high, moderate, and low risk to MPB infestation.

Then an interdisciplinary team, with specialists on timber, silviculture, recreation, wildlife, soils, geology, hydrology, fire, FPM, transportation, and public information, develops an environmentally acceptable plan for reducing losses to the MPB and other insects and diseases--a plan that relates to other forest management activities. This plan provides the manager with guidelines for assigning priorities to timber sales, road building, and cutting schedules in and near lodgepole pine stands.

The rating system may be used on both public and private lands. Hazard criteria can be applied by silviculturists and timber management planners without extensive training. Demonstration areas have been set up in lodgepole pine stands in many areas of the Intermountain Region. Data from the demonstration areas have helped users accept the system as they can review and evaluate the results of cutting strategies based on the stand hazard predicted by the rating system (Emerson 1979).

Performance of the hazard-rating system and management effort's to reduce losses will be monitored and modified as new information becomes available.

LITERATURE CITED

Amman, G. D. 1973. Population changes of the mountain pine beetle in relation to elevation. Environ. Entomol. 2:541-547.

Amman, G. D. 1977. The role of the mountain pine beetle in lodgepole pine ecosystems: impact on succession. p. 3-18. *In* Arthropods in forest ecosystems. W. J. Mattson, ed. Proc. in the Life Sciences. Springer-Verlag, New York.

Amman, G. D. 1978. Biology, ecology, and causes of outbreaks of the mountain pine beetle in lodgepole pine forests. *In* Theory and practice of mountain pine beetle management in lodgepole pine forests. A. A. Berryman, G. D. Amman, and R. W. Stark, eds. Symp. Proc., Coll. Forest., Wildl. and Range Sci., Univ. Idaho, Moscow.

Amman, G. D., M. D. McGregor, D. B. Cahill, and W. H. Klein. 1977. Guidelines for reducing losses of lodge-

pole pine to the mountain pine beetle in unmanaged stands in the Rocky Mountains. 19 p. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. INT-36. Intermountain For. Range Exp. Stn., Ogden, Utah.

Cole, W. E. 1978. Management strategies for preventing mountain pine beetle epidemics in lodgepole pine stands--based on empirical models. *In* Theory and practice of mountain pine beetle management in lodgepole pine forests. A. A. Berryman, G. D. Amman, and R. W. Stark, eds. Symp. Proc., Coll. Forest., Wildl. and Range Sci., Univ. Idaho, Moscow.

Cole, W. E., and D. B. Cahill. 1976. Cutting strategies can reduce probabilities of mountain pine beetle epidemics in lodgepole pine. J. For. 74:294-297.

Cole, W. E., G. D. Amman, and C. E. Jensen. 1976. Mathematical models for the mountain pine beetle-lodgepole pine interaction. Environ. Entomol. 5:11-19.

Crookston, N. L., R. W. Stark, and D. L. Adams. 1977. Outbreaks of mountain pine beetle in lodgepole pine forests--1945 to 1975. 7 p. plus map. Coll. Forest., Wildl., and Range Sci., Univ. Idaho, Bull. 22. Moscow, Idaho.

Emerson, J. R. 1979. Final environmental assessment report, the mountain pine beetle, Flathead National Forest. 79 p. U.S. Dep. Agric. For. Serv., Northern Region, Kalispell, Montana.

Hamel, D. R., and M. D. McGregor. 1976. Evaluation of mountain pine beetle infestations--Lap, Cool, Lang, and Caribou Creek drainages, Yaak Ranger District, Kootenai National Forest, Montana. U.S. Dep. Agric. For. Serv., State and Private Forestry, Missoula, Montana, Rep. 76-6.

Mahoney, R. 1978. Lodgepole pine/mountain pine beetle risk classification methods and their application. *In* Theory and practice of mountain pine beetle management in lodgepole pine forests. A. A. Berryman, G. D. Amman, and R. W. Stark, eds. Symp. Proc., Coll. Forest., Wildl., and Range Sci., Univ. Idaho, Moscow.

Mason, D. T. 1915. The life history of lodgepole pine in the Rocky Mountains. 35 p. U.S. Dep. Agric. For. Serv., Bull. 154.

McDougal, F. W. 1975. The importance of lodgepole pine in Canada. *In* Management of lodgepole pine ecosystems. D. M. Baumgartner, ed. Symp. Proc., Wash. State Univ. Coop. Ext. Serv., Pullman.

McGregor, M. D. 1978. Management of mountain pine beetle in lodgepole pine stands in the Rocky Mountain area. *In* Theory and practice of mountain pine beetle management in lodgepole pine forests. A. A. Berryman, G. D. Amman, and R. W. Stark, eds. Symp. Proc., Coll. Forest., Wildl., and Range Sci., Univ. Idaho, Moscow.

McGregor, M. D. 1978. Status of mountain pine beetle infestations, Kootenai National Forest, Montana, 1977. 12 p. U.S. Dep. Agric. For. Serv., Northern Region, Missoula, Montana, Rep. 78-8.

Roe, A. L., and G. D. Amman. 1970. The mountain pine beetle in lodgepole pine forests. 23 p. U.S. Dep. Agric. For. Serv., Res. Pap. INT-71.

Safranyik, L., D. M. Shrimpton, and H. S. Whitney. 1974. Management of lodgepole pine to reduce losses from the mountain pine beetle. 24 p. Can. Forestry Serv., Forest. Tech. Rep. 1. Pacific Forest Research Centre, Victoria, B.C.

Tackle, D. 1954. Lodgepole pine management in the Intermountain Region--a problem analysis. 53 p. U.S. Dep. Agric. For. Serv., Intermountain For. Range Exp. Stn., Misc. Pub. 2.

Wellner, C. A. 1975. The importance of lodgepole pine in the United States. *In* Management of lodgepole pine ecosystems. D. M. Baumgartner, ed. p. 1-9. Symp. Proc., Wash. State Univ., Coop. Ext. Serv., Pullman.

Wellner, C. A. 1978. Management problems from mountain pine beetle in lodgepole pine forests. *In* Theory and practice of mountain pine beetle management in lodgepole pine forests. A. A. Berryman, G. D. Amman, and R. W. Stark, eds. p. 9-15. Symp. Proc., Coll. Forest., Wildl., and Range Sci., Univ. Idaho, Moscow.

Wikstrom, J. H., 1957. Lodgepole pine--a lumber species. 15 p. U.S. Dep. Agric. For. Serv., Intermountain For. Range Exp. Stn., Res. Pap. 45.

RATING SPRUCE-FIR STANDS FOR SPRUCE BUDWORM VULNERABILITY IN MINNESOTA

Harold O. Batzer and Arthur R. Hastings[1]

Abstract.--A method for rating potential vulnerability of spruce-fir stands to impending spruce budworm attack is given. Thirty-five stands on the Superior National Forest, Minnesota, that were infested with the spruce budworm from 1971 through 1975 were examined in 1977 and 1978. Nine stand characteristics were analyzed. Multiple-regression analyses yielded a model involving two stand variables--preoutbreak balsam fir basal area per acre, and percent nonhost basal area at preoutbreak. Taken together, these variables explained 87 percent of the variation in the per-acre basal area of dead balsam fir.

The condition of the forest is one of the important factors in the development of outbreaks of the spruce budworm, *Choristoneura fumiferana* Clemens. It affects susceptibility of the forest to attack and its vulnerability to injury once an outbreak has begun.

Many investigators have attempted to quantify tree mortality using forest characteristics such as basal area (BA) and volume of fir, age, vigor, species composition, stand density, stand isolation, etc. If these characteristics indicate susceptibility (likelihood of attack) and vulnerability (likelihood of damage), land managers should be able to select the optimum strategy for managing specific spruce-fir stands in advance of a budworm outbreak.

Several recommendations for rating susceptibility or vulnerability have been described, but their application has been scant. This is probably because (1) there may be regional differences in the forest that render universal use inappropriate; (2) factors that influence susceptibility to attack may be different from those influencing vulnerability to injury once an outbreak has started; and (3) balsam fir, the principal host species, has not had a high commercial value, hence less attention has been paid to its management.

We briefly review the previously published recommendations and then present an additional model applicable to northern Minnesota. The earlier schemes are based largely on intuitive groupings of tree and stand characteristics associated with a maturing forest. In recent years more emphasis has been given to mathematically relating stand descriptors to injury.

EARLY EFFORTS

1945--Westveld: Northeastern United States. Vulnerability is equated with volume of balsam fir per acre times BA of the average balsam fir tree.

1946--Balch: New Brunswick. Danger of loss increases with the quantity of even-aged balsam fir, age, and balsam fir content of the balsam-spruce stands. Highly vulnerable stands contain balsam and spruce 60+ years old and average 8+ cords per acre, more than half of which is balsam.

1948--McLintock: Northeastern United States. This scheme evaluates tree risk on a given site as expressed by growth rate.

1949--McLintock: Maine. Hazard is classified according to volume of fir per acre and maturity; e.g., high-hazard stands have 4.0+ cords per acre of mature or overmature fir exceeding 50 to 60 percent of tree numbers.

1951--Morris and Bishop: New Brunswick. Vulnerability is a function of stand densities (crown closure), relative maturity (tree height), and species composition (percent fir). Mortality is associated with age, vigor, and intensity and duration of the outbreak.

1954--Westveld: Northeastern United States. Selected cutting methods are suggested to make spruce fir stands more resistant; a tree classification system is offered as a guide for selecting trees to cut or retain.

1956--Graham: Michigan and Minnesota. Hazard is assigned largely on maturity of balsam fir and relative crown position of fir when mixed with hardwoods.

1956--Bean and Batzer: Lake States. Risk is assigned on the basis of age, density (volume), composition (percent balsam fir), area of stands, and vigor.

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1969--Batzer: Minnesota. A multiple-regression equation predicts percent balsam fir dead using three stand variables: percent BA in spruce, percent BA in nonhost species, and total balsam fir BA in ft^2/acre.

1972--van Raalte: New Brunswick. Susceptibility is evaluated on the basis of five criteria: species composition, stand age-height, stand density, isolation, and topography.

Two articles with substantial data (Turner 1952 and McLintock 1955) might have yielded multiple-regression models had computer science been available then.

METHODS

During the summer of 1977, 29 stands were selected in the southeastern part of the Superior National Forest of Minnesota. These stands had severe infestation in the two preceding years and some infestation by the spruce budworm since 1971. In 1978, six more stands were added. An attempt was made to distribute the sample stands over a range of fir mortality and stand conditions. Each stand was sampled by a cluster of four .04-ha (1/10-acre) circular plots; each plot was 40 m (2 chains) in a cardinal direction from a point mechanically selected to be at least 80 m into the stand. All trees greater than 8.9 cm (3.5 in) at breast height were measured to the nearest 0.1 inch.

RESULTS AND DISCUSSION

In a preliminary screening we correlated dead balsam fir BA with a variety of stand variables (table 1). The most important were original (at time of budworm attack) balsam fir BA and percent BA in nonhost species (other than balsam fir or spruce). The multiple-regression analyses with these variables resulted in the model

$$D = .97\ OB - .42\ \%NH - 4.1,$$

where

D = dead balsam fir BA per acre

OB = original balsam fir BA per acre

NH = nonhost BA per acre, and

$R^2 = .87$; SE = 12.5; n = 35. (*See* figure 1.) Dead fir increased with higher initial fir BA and decreased with more nonhost species (table 2).

The relations between balsam fir mortality, fir density, and percent nonhost BA are similar to those reported by Batzer (1969) and Turner (1952) in stands where balsam fir was intermediate in crown position. The new model explains more of the variation in mortality than did the 1969 model ($R^2 = .87$ *v.* .56). However, spruce was not a significant variable in the current model, whereas it was important in the 1969 model. Reasons for this are obscure, but the finding is consistent with

Table 1.--Selected stand variables of 35 spruce-fir stands and correlation coefficients from analyses between dead balsam fir basal area and other stand variables

Stand variable	Mean	Range	Correlation coefficient (r)
Dead balsam fir basal area[1]	48	2 - 116	-
Basal area in balsam fir[1]	66	21 - 120	.91**
Basal area in nonhost species[1]	35	0 - 104	-.37*
Basal area in spruce[1]	15	0 - 64	-.21
Basal area for all species[1]	115	69 - 184	.46**
Percent balsam fir basal area	56	29 - 91	.84**
Percent nonhost basal area	28	0 - 57	-.61**
Percent spruce basal area	14	0 - 56	-.29
Age of balsam fir (years)	49	37 - 73	-.17
Site index for balsam fir[2]	53	34 - 74	.01

[1] In ft^2/acre.

[2] Feet at age 50.

*r = .33 at 5 percent

**r = .43 at 1 percent.

Table 2.--Dead balsam fir basal area after 5 years of attack by the spruce budworm estimated from original balsam fir basal area and percent nonhost basal area, trees 4 inches in d.b.h. and up

Percent nonhost basal area	Original balsam fir, basal area in ft²/acre 20	40	60	80	100	120
	Dead balsam fir, basal area ft²/acre					
0	15	35	54	73	93	112
10	11	30	50	69	89	108
20	7	26	46	65	84	104
30	3	22	41	61	80	100
40		18	37	57	76	95
50		14	33	52	72	91
60		9	29	48	68	87

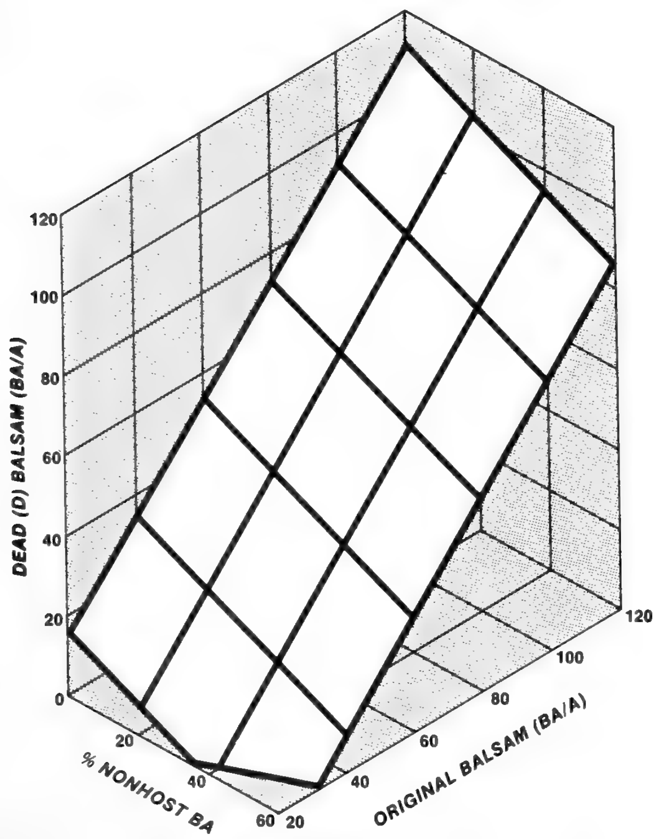

Figure 1.--The relation between dead (D) balsam BA per acre and two stand variables: original balsam fir (OB) BA per acre, and percent nonhost (NH) BA per acre from the regression equation (see text).

Turner (1952), who found a tendency for fir mortality to increase with the amount of white spruce in the softwood types. No increase in fir mortality with the amount of white spruce was noted in the mixedwood-softwood types in Ontario. Only half of the spruce-fir stands in the present study were more than 75 percent softwood; in the 1969 study nearly two-thirds were predominantly softwood.

Data for the present study came from the southeast portion of the forest, while in the 1969 study data came from the northwest portion of the forest. A drought in 1976 may have accelerated the fir mortality.

Site index or age of balsam fir were not important variables (table 1).

These findings confirm the relative importance of balsam fir and nonhost tree densities to fir mortality. They offer the land manager a tool to estimate potential loss from spruce budworm in spruce-fir stands. The differences between the present and the 1969 model emphasize the importance of regional as well as temporal differences in spruce budworm outbreaks.

RECOMMENDATIONS

An assessment of potential loss from spruce budworm attack may be made during routine compartment examination or remeasurement, or when concern exists over an impending spruce budworm infestation. Those stands whose values estimated from the equation or read from table 2 are larger than can be accepted by the manager should be harvested first. If a spruce budworm outbreak has already begun, the rating will indicate which stands should be included in an accelerated harvesting program. If additional time is needed before harvesting, insecticidal (chemical or bacteriological) sprays may be used to keep trees alive, provided that costs and environmental impacts do not exceed the benefits.

LITERATURE CITED

Balch, R. E. 1946. The spruce budworm and forest management in the Maritime Provinces. 7 p. Can. Dep. Agric., Div. Entomol. Proc., Pub. 60.

Balch, R. E. 1946. Spruce budworm--map showing relative susceptibility in

various areas of New Brunswick. Can. Dep. Agric., For. Insect Investigations Bi-Mon. Prog. Rep. 2(3):1.

Batzer, H. O. 1969. Forest character and vulnerability of balsam fir to spruce budworm in Minnesota. For. Sci. 15: 17-25.

Bean, J. L., and H. O. Batzer. 1956. A spruce budworm risk-rating for the spruce fir types in the Lake States. 2 p. U.S. Dep. Agric. For. Serv., Tech. Note LS-453. Lake States For. Exp. Stn., St. Paul, Minn.

Graham, S. A. 1956. Hazard rating of stands containing balsam fir according to expected injury by spruce budworm. 1 p. Univ. Mich., School of Nat. Resour., Mich. For. Note 13.

McLintock, T. F. 1948. Evaluation of tree risk in the spruce fir region of the Northeast. 7 p. U.S. Dep. Agric. For. Serv., Res. Pap. NE-16. Northeast. For. Exp. Stn., Upper Darby, Pa.

McLintock, T. F. 1949. Mapping vulnerability of spruce fir stands in the Northeast to spruce budworm attack. 20 p. U.S. Dep. Agric. For. Serv., Res. Pap. NE-21. Northeast. For. Exp. Stn., Upper Darby, Pa.

McLintock, T. F. 1955. How damage to balsam fir develops after a spruce budworm epidemic. 18 p. U. S. Dep. Agric. For. Serv., Res. Pap. NE-75. Northeast. For. Exp. Stn., Upper Darby, Pa.

Morris, R. F., and R. L. Bishop. 1951. A method of rapid forest survey for mapping vulnerability to spruce budworm damage. For. Chron. 27:171-178.

Turner, K. B. 1952. The relation of mortality of balsam fir, *Abies balsamea* (L.) Mill., caused by the spruce budworm, *Choristoneura fumiferana* (Clem.), to forest composition in the Algoma Forest of Ontario. 107 p. Can. Dep. Agric., Agric. Publ. 875. Ottawa.

van Raalte, G. D. 1972. Do I have a budworm-susceptible forest? For. Chron. 48:190-192.

Westveld, M. 1945. A suggested method for rating the vulnerability of spruce-fir stands to budworm attack. 4 p., processed. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Westveld, M. 1954. A budworm vigor-resistance classification for spruce and balsam fir. J. For. 52:11-24.

RATING SOUTHERN PINE BEETLE HAZARD BY AERIAL PHOTOGRAPHY

G. N. Mason, R. R. Hicks, Jr., C. M. Bryant V., M. L. Mathews, D. L. Kulhavy, and J. E. Howard[1]

Investigations of site/stand conditions relating to attack severity by the southern pine beetle have resulted in recommendations for SPB prevention through silvicultural stand treatment. Rapid implementation of many stand hazard-rating systems over broad areas has been limited due to specialized soil, site, and tree data requirements available only from specific site-by-site visit and measurement. The purpose of this project was to develop and verify an SPB stand hazard-rating procedure for large areas using conventional aerial photographic procedures.

Efforts were initiated at Stephen F. Austin State University in 1973 to quantify associations between SPB infestations and host-site/stand conditions. Field crews collected data representing over 30 site, stand, and tree parameters in approximately 1,140 infested and baseline plots. Hicks et al. (1980) has presented a mathematical model predicting stand susceptibility from these data. Concurrent with these studies, beginning in 1976, ten 18,200-acre test blocks, randomly distributed through the east Texas outbreak area, were stand mapped using NASA 1/60,000 infrared photos with small-format aerial photo sampling supplement. Photo selections coincided with peak SPB activity and historical record availability (1972-76). Six photo-identifiable variables were included in the mapping project: basal area/acre (BA), total stand height, species composition, crown closure, average tree diameter (d.b.h.), and topographic position. Ground and photo results have been integrated to produce a technique for broad-scale SPB stand hazard classfication, with field verification on 182,000 acres of east Texas timberlands in mixed ownership.

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MODEL DEVELOPMENT AND VERIFICATION

We developed a photo-applicable discriminant function model using reclassified and coded data from Hicks' east Texas site/stand plots (approximately 500 infested and 500 baseline). Input data included percent pine stocking (six categories, 20 percent classes); percent crown closure (five categories, 20 percent classes), d.b.h. (four categories, 3-inch classes), average stand height (four categories, 40-ft^2 classes), topographic position (five categories)[2]. Using coded, photo-realistic classes and discriminant function analysis, we found BA, height, and landform to best distinguish infested from baseline conditions. The equation for this discrimination is

$$HAZ= -5.90 + 1.09BAC + .65HTC + .56LDC$$

where: HAZ=Stand susceptibility rating

<-1.82	very low
-1.82 to -0.59	low
-0.059 to +0.54	moderate
0.54 to 1.12	high
>1.12	very high

BAC = Basal Area Code
HTC = Height Code
LDC = Landform Code

Statistical classification correctness = 72.8 percent.

Based on these results, BA, height, and landform combinations for each stand in the 182,000-acre test area were rated into hazard classes, the number of acres in each polygon determined, and the acreages summarized by test block and hazard class. We determined total area in each hazard class in the northern portion of the outbreak area (four blocks nearest the counties of ground data collection). These calculations revealed a predominance of moderate-hazard stands, with relatively few very low- or very high-hazard stands.

[2] Data input values for each category are presented under RATING STAND SUSCEPTIBILITY (table 1).

Locations of SPB spots (1973-78 Texas Forest Service data[3]) were overlain by size and date to compare hazard classification with actual infestation occurrence. Spot frequency was observed to be directly related to habitat availability. The greatest number of spots occurred in moderate-hazard stands, with few in very low- and very high-hazard categories. However, when all classes were equated on a 1,000-acre basis, the preference for conditions associated with very high-hazard stands was outstanding. The trend was more pronounced when total number of controlled trees was considered.

The same approach was then repeated to test the applicability of the model in the southern portion of the outbreak area (southern six test blocks). We found similar acreages and spot distribution frequencies. Trends in spots and trees per 1,000 acres of hazard class were less pronounced than in the northern blocks, but

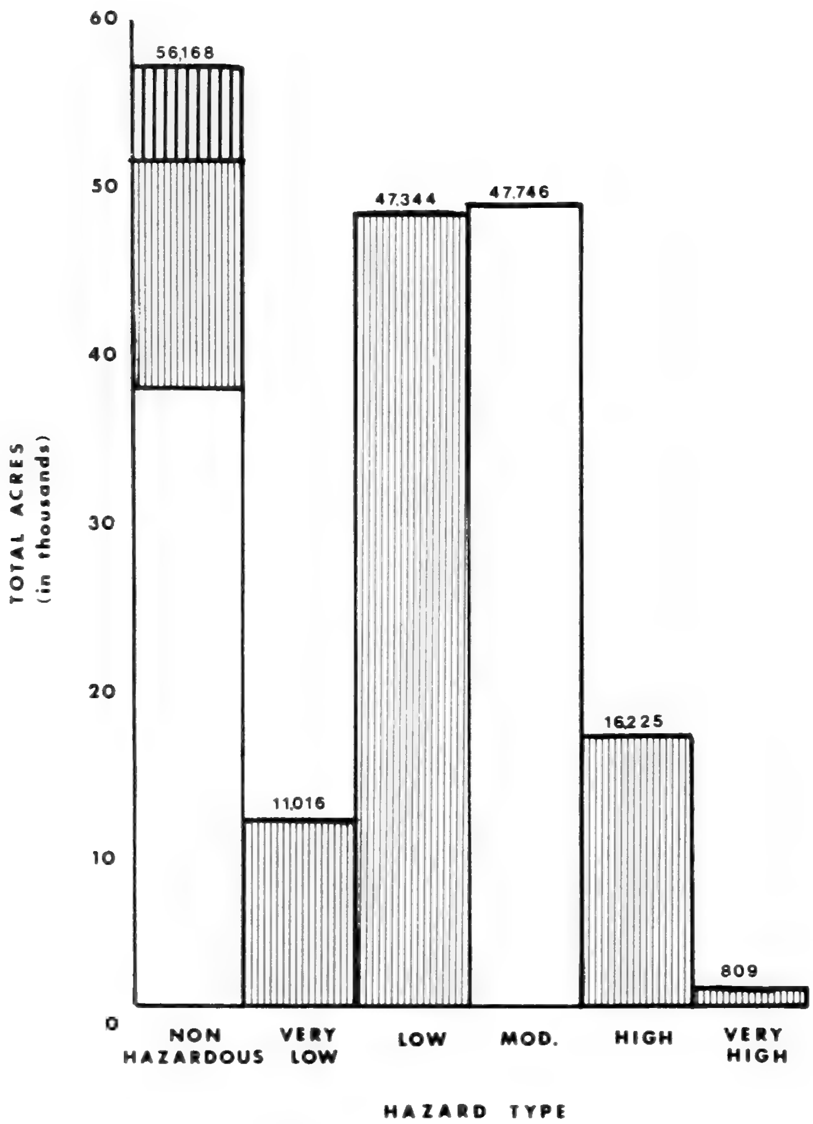

Figure 1.--Summation of total acreage in all (10) test areas by hazard type, open, hardwood, and clearcut categories.

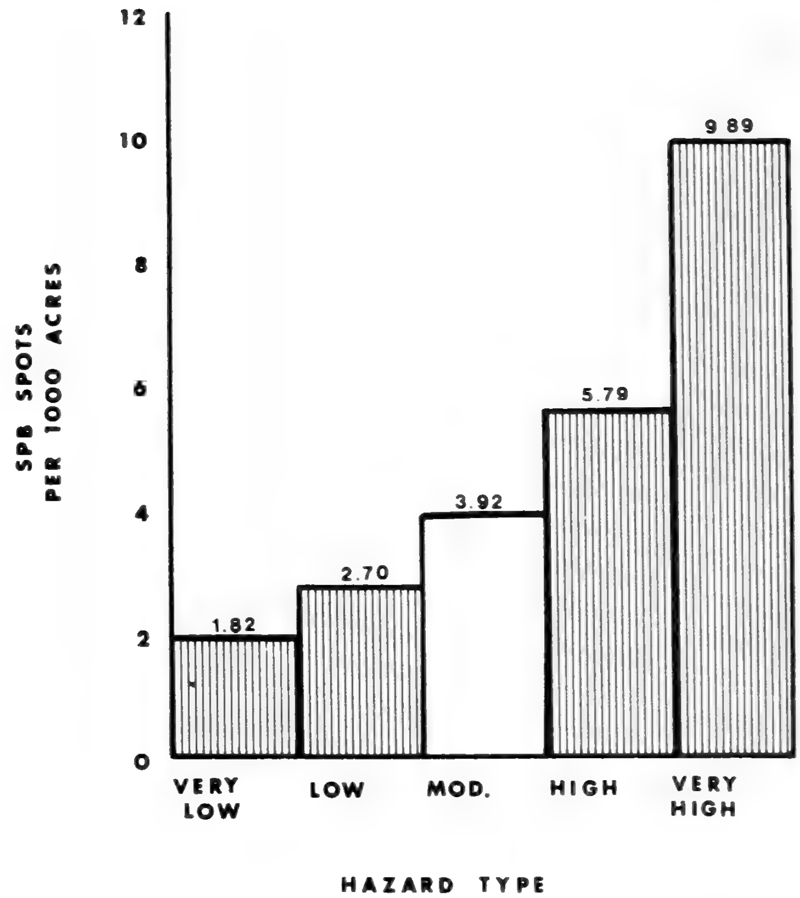

Figure 2.--Number of spots occurring per 1,000 acres of hazard class in all (10) test areas (1973-78).

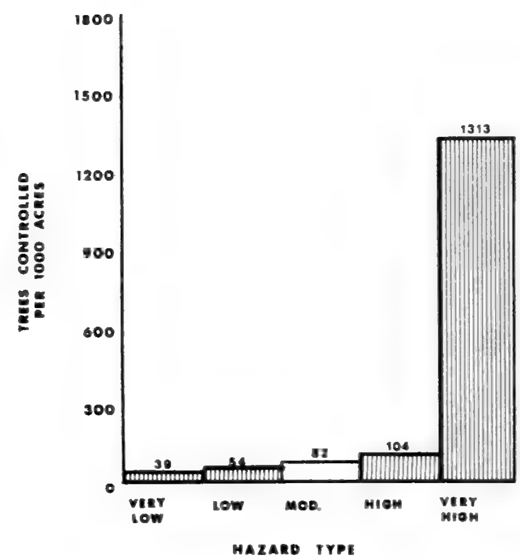

Figure 3.--Number of trees controlled per 1,000 acres of hazard class in all areas (1973-78).

very similar. Next we merged data from both northern and southern blocks with similar results for the total study area (figs. 1-3).

Associations between beetle activity and hazard assignments were again very strong. Differences between hazard classes for north, south, and combined com-

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[3] Forest Pest Control Section, Lufkin, TX 75962.

parisons were all significant ($\chi^2 < .01$). These combined data were used to derive recommendations and guidelines for Texas.

Five-year loss projections (based on approximately 500 spots occurring within the test area from 1973 through 1978) were developed as added input to aid in pest management decisionmaking. This stand-rating system, with loss projections, has been incorporated into a "Texas SPB Hazard Rating Guide."[4] Although the guide was designed to be applied using aerial photography in east Texas, it works equally well with field observation or existing stand-type maps where appropriate information is available. Additional tests have recently been completed which support its suitability for for use in Louisiana (Autry 1980).

RATING STAND SUSCEPTIBILITY

Pest management activities should complement, rather than compete with existing forest management programs. Ease of hazard rating implementation is dependent upon availability of existing information. Several approaches are discussed below, in order of increasing difficulty (i.e., lack of existing resource data).

Application from Existing Stand Type Maps and/or Stand Data

Most managed forest ownerships maintain tract survey, management unit, and stand type maps for which inventory information is available. These records generally include the required tree height, BA, and landform hazard-rating variables, or similar data from which they can be derived. Computer storage and retrieval offers acquisition convenience and continuous update capability, and represents the ideal data base situation for SPB hazard rating. Stands may be classed manually from computer printouts, directly from stand maps, or automatically after entering the appropriate rating equation. This approach has been initiated for the USDA National Forest Continuous Inventory of Stand Conditions system (CISC), is currently undergoing final tests on the Kisatchie NF in Louisiana (Lorio 1978, Lorio and Sommers 1980), and has recently been shown to be applicable to National Forest lands in Texas (Autry 1980).

Application Using Small-Scale Aerial Photographs with Resource Photography Supplement

This is probably the simplest approach for forest ownerships not having stand maps and inventory data, but for which medium-scale aerial photo coverage is available.

When selecting general-use aerial photography, we tend to seek large-scale, low-altitude photography exhibiting abundant ground detail. But in classifying stand types from these photos, the old adage "you can't see the forest for the trees" is very appropriate. Large- and medium-scale photos generally reveal too much *tree* information, making it difficult to distinguish *stands*. Our task may be simplified using a bilevel approach in which *stands* are easily recognized as tone and textural patterns on small-scale (1/40,000-1/120,000) color-infrared photos. Sample findings are then extrapolated to similar patterns elsewhere on the small-scale interpretation.

Generalized procedure:

1. Locate small scale (1/40,000 to 1/120,000) color-infrared stereo coverage.[5]

   a. 1/60,000 scale is common and preferred (it is also the approximate scale of USGS 15-minute topographic quad sheets [1/62,500], which may be used for LANDFORM classification and as a base map standard).

   b. Late fall and winter (leaf-off) photography offers easiest hardwood-conifer distinction.

   c. Transparencies offer greater interpretation detail than prints, but tradeoffs for convenience and possible future use of prints should be considered.

2. Acquire photos, check coverage and quality (tonal and textural differences and adequacy of detail).

3. Delineate stands (areas of homogeneous tone, texture, pattern, etc.) on acetate overlays. Minimum stand size will depend upon management policies (10- to 25-acre minimums are common).

4. Select representatives of each tone and textural group for more detailed examination on medium-scale photography.

5. Observe sample stands on medium-scale photos; classify each by BA and height class according to table 1.

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[4] Available from SFASU School of Forestry, Nacogdoches, TX.

[5] Information on aerial photo availability for Texas may be obtained from Texas Natural Resource Information System, TNRIS Systems Central, P. O. Box 13087, Austin, TX 78711, (512) 475-3321; elsewhere in the South, contact the EROS Applications Assistance Facility, NSTL, Bay St. Louis, MS 39520, (601) 688-3541.

Table 1.--Categories and map codes for SPB aerial photo hazard classification

Basal area/ acre (ft^2)	Stand height (ft)	Landform	Classification code
< 40	< 50	Ridge	1
41-80	51-75	Side slope	2
81-120	76-100	Bottom	3
> 120	> 100		4

6. Check representatives of each type on the ground to evaluate interpretation accuracy; adjust as necessary.

7. Based on sample stands, extrapolate stand code information to all stands of similar tonal and textural appearance on small-scale photos.

8. Draft preliminary stand maps, field check a number of stands (10 to 15 percent) as a final test of map accuracy.

9. Identify landform classes on USGS topo maps. Fifteen-minute topo quads (1/62,500) approximate the scale of 1/60,000 high-altitude photography and simplify the merging of stand and landform information. Fifteen-minute quads may not be available for all areas; 7½-minute quads offer greater detail but require scale adjustment.

Landform classification is more or less subjective. Required classification categories are RIDGE, SIDESLOPE, and BOTTOM, reflecting soil drainage conditions and site quality more than elevational position. Landform positions, relative to local topographic conditions, are identified on topo quads by outlining selected contour lines to represent each of the three classes.

10. Combine stand (BA/A and height) maps with landform maps to produce stand-landform polygon maps containing the required BA, height, and landform hazard-rating codes.

11. Rate stands using the mathematical equation or circular "SPB Hazard Rating Guide."

12. Prepare final hazard maps.

Application Using Small-Scale Photography with 35-mm Aerial Photo or Ground Cruise Supplement

For small ownerships, mixed ownerships, or other areas where medium-scale aerial photography is not adequate to supplement high-altitude stand interpretations, 35-mm vertical or hand-held oblique supplementary photography or extensive ground checks may provide necessary stand detail information. Mapping would proceed as above, with sample stand detail derived from one of the alternate methods. Information from low-level flights may be recorded as visual observations. Preferably, it should be photographed to allow direct and repeated subsequent comparisons with small-scale interpretations. Aerial camera mounts (35 mm) are available and provide vertical photos at predetermined, controlled scales (Mason and Mathews 1979). Hand-held oblique photos, taken through the plane window, offer adequate interpretative information but have the disadvantage of scale variation and unknown photo orientation.

If aerial flights and photography are impractical, field crews may visit sample stands to collect needed classification information. Ground observation is more time consuming and cannot provide valuable aerial perspective when comparing stand detail to high-altitude interpretations.

Stand coding, draft maps, topo maps, and hazard classification would proceed as previously described.

Application from Resource Photography Only

Many organizations have existing medium-scale resource photography and may not wish to acquire additional small-scale photos. Some interpreters prefer working with medium-scale photos, but the advantages of small-scale stand delineation have been previous discussed.

Stand mapping from medium-scale photos would proceed as described above, with the exception that stand delineation and stand detail would be acquired from the same photo source.

Application from Ground Cruising

In the absence of aerial photography, or for individual tracts of particular concern or small ownership, ground observers can directly determine SPB hazard.

Although the circular "SPB Hazard Rating Guide" was developed for use with aerial photography, it is equally applicable in the field. The difficulty in applying any hazard-rating system on the ground is recognizing and establishing stand boundaries, and determining the number of points within a stand which should be observed to adequately represent average conditions. Standards applicable to timber inventory should be used in ground hazard classification.

DISCUSSION

The rewards of SPB susceptibility assessment are varied. Most simply, it

allows an evaluation of potential risk to determine what portion of an area which can be considered "safe" and what portion must be considered potentially "dangerous." This knowledge, coupled with loss projections (Hicks 1980 and Mason's Texas "SPB Hazard Guide") may be used to better plan and budget timber- and pest-management activities.

Just as prescribed burning has been used as a tool to reduce fire fuel hazard, knowledge of the significance of high SPB hazard provides the opportunity for insect hazard reduction. High- and very high-hazard stands have been shown to have greater loss potential than lower hazard classes. Through proper thinning, higher-hazard stands can be converted to a lower susceptibility level.

Further reduction of SPB risk can be attained through beetle population removal. Stand thinning is a very important long-term, silvicultural preventative treatment. However, immediate direct risk reduction may be approached by removing the potential buildup population. Our observations suggest that the beetles depend strongly upon optimal host-habit conditions during periods of low (endemic) activity. When activity is low, most SPB spots appear in very high-hazard (optimal habitat) areas. As activity increases, spots become normally distributed among all habitat types, and as the populations subside, spots again appear in very high-hazard stands (fig. 4).

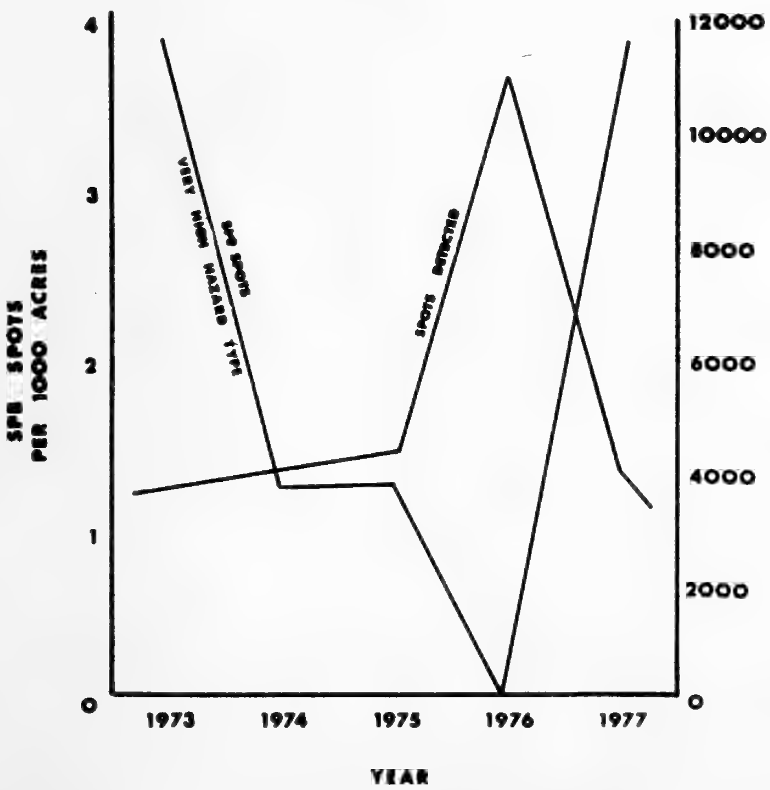

Figure 4.--Relationship between total SPB spots detected and number of spots occurring in very high-hazard stands.

These areas of high beetle concentration during endemic periods may serve as "population reservoirs." It is much more logical to make the attack when the enemy is suppressed and weak than when it is in its most vigorous and most powerful state (i.e., during an SPB epidemic). Our problem in the past has been an inability to locate infestations when general beetle levels were suppressed. Removal and utilization of very high-hazard "reservoir" stands during periods of low SPB activity should serve to remove parent sources from which future epidemics will develop.

SPB surveillance and evaluations are necessary during endemic periods while survey costs continually increase. By concentrating endemic survey efforts in reservoir stands, we should detect activity buildup at its earliest stage. If no activity is detected in the most susceptible areas, there should be little elsewhere. As outbreaks begin to appear in the more susceptible areas, surveys can be expanded to include the entire area of concern.

Finally, hazard identification enables us to assign control priority. Often the best control is no control. Spot development and impact are closely related to habitat conditions (Billings and Pase 1979). Spots often develop in stressed trees, or in small, high-susceptibility pockets within low-hazard stands. However, as the spot expands into the less desirable habitat, activity subsides and the spot fails. A good control alternative for spots in these areas is to wait 2 to 3 weeks and reevaluate their status. On the other hand, similar spots surrounded by high-hazard stand conditions have a high probability of continued expansion and should be acted upon immediately.

SPB hazard rating serves many purposes, ranging from an overall better understanding of management inventory and responsibilities to reduction of SPB suppression costs. We believe that with the availability of existing data in most organizations, a hazard-rating effort is warranted, worthwhile, and extremely compatable with current management programs. The user should be reminded that *all* infestations do not occur in *high*-hazard stands, and all high-hazard stands do not become infested. Because of relative abundance of low and moderate types, there may be many spots occurring in these stands. However, due to more rapid population and spot development rates within high-hazard stands and the greater value of larger trees, which characterize the high-hazard type, these areas will support a major portion of the SPB impact.

LITERATURE CITED

Autry, G. L. 1980. Comparing southern pine beetle hazard rating systems for Texas and Louisiana. Unpublished M.S. thesis. Stephen F. Austin State Univ., Nacogdoches, Tex. 55 p.

Billings, R. F., and H. A. Pase, III. 1979. A field guide for ground checking southern pine beetle spots. 18 p. U.S. Dep. Agric. For. Serv., Agric. Handb. 558. Comb. For. Pest. Res. Develop. Prog., Pineville, La.

Hicks, R. R., Jr., J. E. Howard, K. G. Watterston, and J. E. Coster. 1980. Rating forest stand susceptibility to southern pine beetle in east Texas. For. Ecol. Manage. 2:269-283.

Lorio, P. L., Jr. 1978. Developing stand risk classes for the southern pine beetle. 9 p. U.S. Dep. Agric. For. Serv., Res. Pap. SO-144. South. For. Exp. Stn., New Orleans, La.

Lorio, P. L., Jr., and R. A. Sommers. 1981. Stand risk classification for the southern pine beetle with available resource data. *In* Hazard-rating systems in forest insect pest management: symposium proceedings. [Athens, Ga., July 1980.] R. L. Hedden, S. J. Barras, and J. E. Coster, coords. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. WO-27.

Mason, G. N., and M. L. Mathews. 1979. Camera mount assembly for small format aerial photography. South. J. Appl. For., 3:152-154.

DEVELOPMENT OF A STAND SUSCEPTIBILITY CLASSIFICATION FOR DOUGLAS-FIR BEETLE

Malcolm M. Furniss, R. Ladd Livingston, and Mark D. McGregor[1]

INTRODUCTION

The Douglas-fir beetle (DFB), *Dendroctonus pseudotsugae* Hopk., occurs throughout most of the distribution of its principal host, Douglas-fir (DF), *Pseudotsuga menziesii* (Mirb.) Franco (fig. 1). Western larch, *Larix occidentalis* Hook, is also infested, but progeny survive only in felled larch.

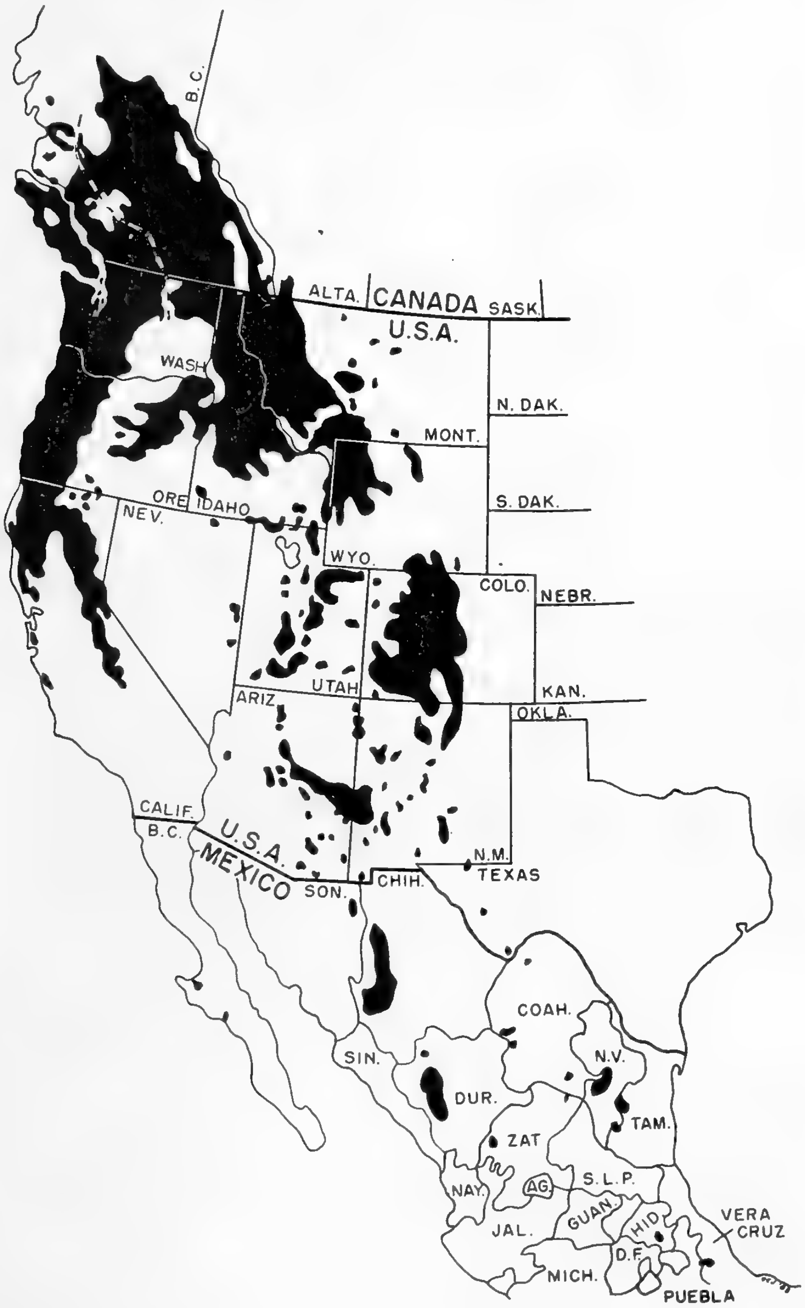

Figure 1.--Geographic distribution of Douglas-fir.

The DFB is univoltine, overwintering mainly as callow adults (Furniss and Orr 1978). It is a robust flier, taking flight early in spring as air temperature warms above 65° F. We have observed flights of 6 hours' or more duration at an average velocity of 2.5 mph (4 km/hr) on flight mills. Thus, DFB are capable of dispersing several kilometers in a single flight, permitting them to reach susceptible stands at some distance from population sources.

Much literature about the beetle has been compiled (Furniss 1979), including information related to host susceptibility. However, no susceptibility classification has been published relating probability of mortality to descriptors of trees, stands, or sites.

This paper deals, in order of emphasis, with the natural basis for a susceptibility classification, field methodology, and analyses. This information was developed during long-term research from examinations of many hundreds of trees, particularly in Idaho, and from the cited works of others. Nonetheless, we have only recently begun a concerted effort to develop a more holistic approach to defining mathematically the probabilities of mortality, given various stand data. Thus, at the time of this symposium, we have not concluded fieldwork and our probability example is based on a limited data set. We believe, however, that the natural basis for the classification and the field methodology will be of interest and will foster communication with others.

When our present work is completed, we will compare in a future publication the probabilities of mortality derived from a more adequate sample base from stands representing a broader range of edaphic, climatic, and floristic conditions. We are confident that the outcome will provide protection specialists and resource managers with better means of classifying stands in need of silvicultural treatments and other practices to prevent DFB from killing trees. Concurrently, we hope to provide an avenue for understanding the processes responsible for or related to presence or absence of DFB infestation.

NATURALISTIC BASIS FOR CLASSIFICATION

In this section, we present information on beetle behavior, characteristics

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of infested trees and groups, and predisposing agents. That information forms the natural basis for our seeking to relate descriptors of sites and stands to DFB susceptibility.[2]

Aggregation Behavior

The DFB typically attacks groups of trees, not single trees. Group killing results from aggregation of beetles to pheromones secreted by unmated females that have begun invading their hosts (Pitman and Vité 1970, Pitman et al. 1975). Attractiveness of those pheromones is synergized by resin odors, primarily α-pinene (Furniss and Schmitz 1971). Attraction is terminated when the antiaggregative pheromone MCH is released after mating (Rudinsky and Ryker 1976).

Number of trees killed per group varies with abundance of beetles and extent of susceptible trees. During outbreaks, infested groups increase in size: a single group may include well over 100 trees. Normally groups do not enlarge after the year of attack because the beetles disperse to more susceptible units of surrounding stands. This discrete pattern may be altered somewhat when susceptible stands are contiguous or extensive, beetles are exceptionally abundant, or root disease is prevalent.

Because aggregative pheromones cause beetles to attack groups of trees, we are developing a stand classification rather than an individual tree classification. However, data are taken from individual trees in developing the stand classification.

Host Specificity

The species and chemical characteristics of natural hosts of the DFB provide insight into what makes a tree or stand susceptible. Only two species of trees are known to produce DFB broods in nature: Douglas-fir and western larch. Hopkins (1921) listed big cone Douglas-fir (*Pseudotsuga macrocarpa* [Vasey] Mayr) as a host in southern California, but that record cannot be verified. In Chihuahua, Mexico, *Pseudotsuga flahaulti* Flous is a host (Furniss 1981), although it is doubtfully distinct from *P. menziesii* (Little 1979).

Sometimes, western larch trees are attacked--always unsuccessfully--when growing among DF that are under DFB attack (fig. 2). Freshly felled larch is a good host, though. DFB broods emerge from larch at rates equal to broods from DF (Furniss 1976).

Figure 2.--Unsuccessful resin-impregnated egg galleries in live western larch.

Live DF and western larch have similar monoterpenes in their resin (Hanover and Furniss 1966, Stairs 1968). Both possess a large amount of α-pinene, and the average amounts of four other monoterpenes are similar. As noted earlier, α-pinene greatly increases attractiveness of aggregative pheromones.

It seems reasonable to explain the infestation of live western larch by the presence of intermingled odors from neighboring attacked DF and the similarity of the trees' monoterpene content. That is, beetles arrest on trees in the vicinity of attractant odors; some arrested females are stimulated to construct egg galleries by "familiar" monoterpenes present in larch resin. But we still do not know why broods fail to survive in live larch. Solving that puzzle may contribute to developing improved preventive methods, per-

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[2] We distinguish between susceptibility to attack (which we define as attractiveness of the host tree) and susceptibility to *successful* attack. The distinction will be apparent in subsequent discussion.

haps by genetic selection of Douglas-fir trees containing the resistant mechanism that is universal in live larch.

Susceptibility of Attacked Trees

We recognize three categories of susceptibility of trees in infested groups: susceptible, intermediate, and resistant. Susceptible trees are readily killed. Their egg galleries are free of resin, and their foliage discolors within approximately 1 year. Such trees yield DFB progeny at the highest rates. Intermediate trees eventually die, apparently from inoculation with fungi carried by beetles (Harrington et al. 1981, Rumbold 1936). Foliage of some trees of this category discolors more slowly, sometimes in the second year following attack. Resistant trees survive; their galleries are impregnated with resin and eventually are covered over by callous growth (Belluschi et al. 1965) (fig. 3).

Table 1 compares the characteristics of 739 attacked trees in all three categories, in western Montana. The trees averaged 188 years in age. We obtained similar data from somewhat younger trees (average 111 years) in northern Idaho (Furniss et al. 1979). An average of 29 percent of those trees were attacked unsuccessfully, whereas 22 percent of the Montana trees survived attack.

Thus, in *unmanaged* stands, beetles attack groups of nearly mature or older trees. Generally attacks are more dense and successful in trees that are larger, more dominant, and more productive of resin (fig. 4 A and B). Less dominant trees are smaller and tend to be poor producers of resin (fig. 4 C). We theorize that good resin producers may be inherently more resistant (higher threshold of successful attack density) but may be killed at a higher rate because they attract more beetles. Poor producers of resin may have a lower threshold of successful attack density, but that threshold is attained less often because the necessary resin odor is not present to synergize the aggregative pheromone of females that attack them (Furniss and Schmitz 1971). Concentration of monoterpenes varies greatly between trees (Hanover and Furniss 1966). For example, α-pinene--a strong synergist of aggregative pheromone--varies from 10 to 52 percent of the oleoresin

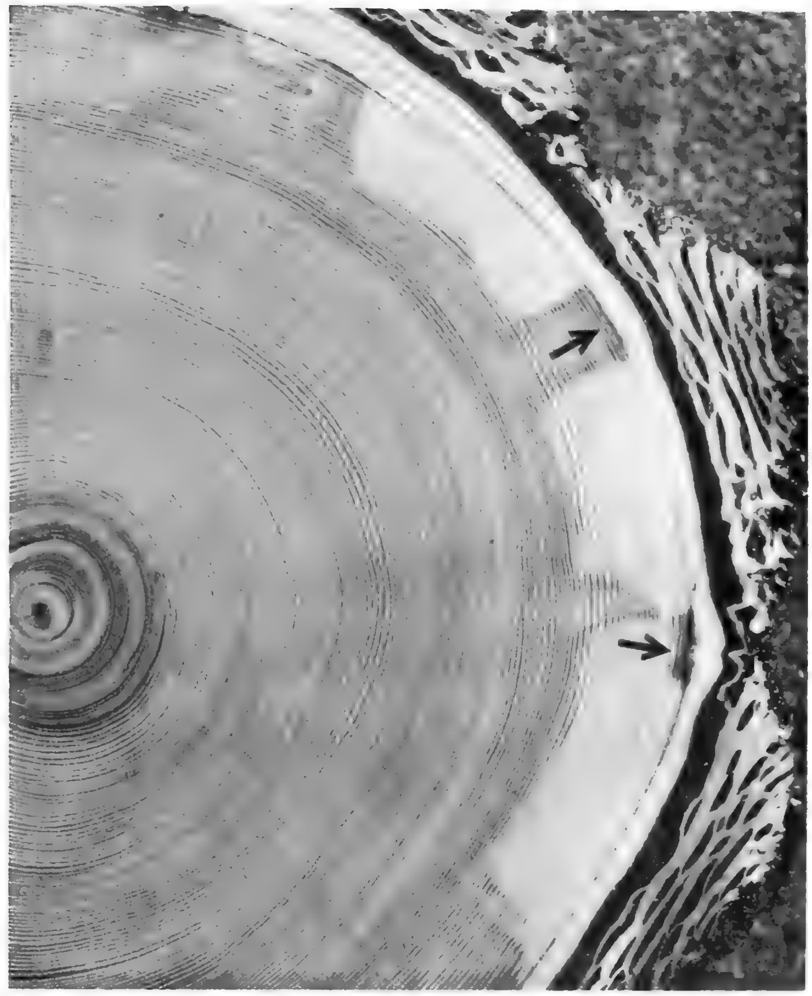

Figure 3.--Unsuccessful egg galleries in Douglas-fir covered over by callous growth. Note stimulation of growth rate in response to wounding.

Table 1.--Frequencies and characteristics of categories of attacked trees, western Montana, 1963

Category	Percent	d.b.h.	10-year growth	Density of attacks[2]
		inches	inches	number/ft^2
Susceptible	48	17.13 (356)[1]	0.285 (28)	10.9 (5)
Intermediate	30	16.21 (221)	0.274 (33)	5.2 (7)
Resistant	22	12.84 (162)	0.237 (27)	3.4 (27)

[1] Figures in parentheses are number of observations.
[2] Density of attack was determined by removal of bark from stems and counting all egg galleries.

content; 3-carene, a nonattractant, varies from 0 to 7 percent. We speculate that a tree with maximum α-pinene and minimum 3-carene content would aggregate more beetles if attacked than would a tree of minimum α-pinene and maximum 3-carene content.

Stand Characteristics

Density

We have never seen a DFB outbreak in residual stands after any kind of commercial cutting. In northern Idaho, representative stands (fig. 5) in which DFB have killed trees contained a majority of DF and were stocked at 80 to 124 percent of normal (241 to 361 ft^2/acre) (Furniss et al. 1979, and unpublished data).

Major factors involved in the susceptibility of dense DF stands are moisture stress and shaded stem environment. The relationship between moisture stress and tree mortality caused by bark beetles seems universal and is documented in literature (Furniss 1979, Rudinsky 1962 and 1966). A less well publicized factor is shading of stems in dense stands. DFB avoid the hot, sun-exposed portion of

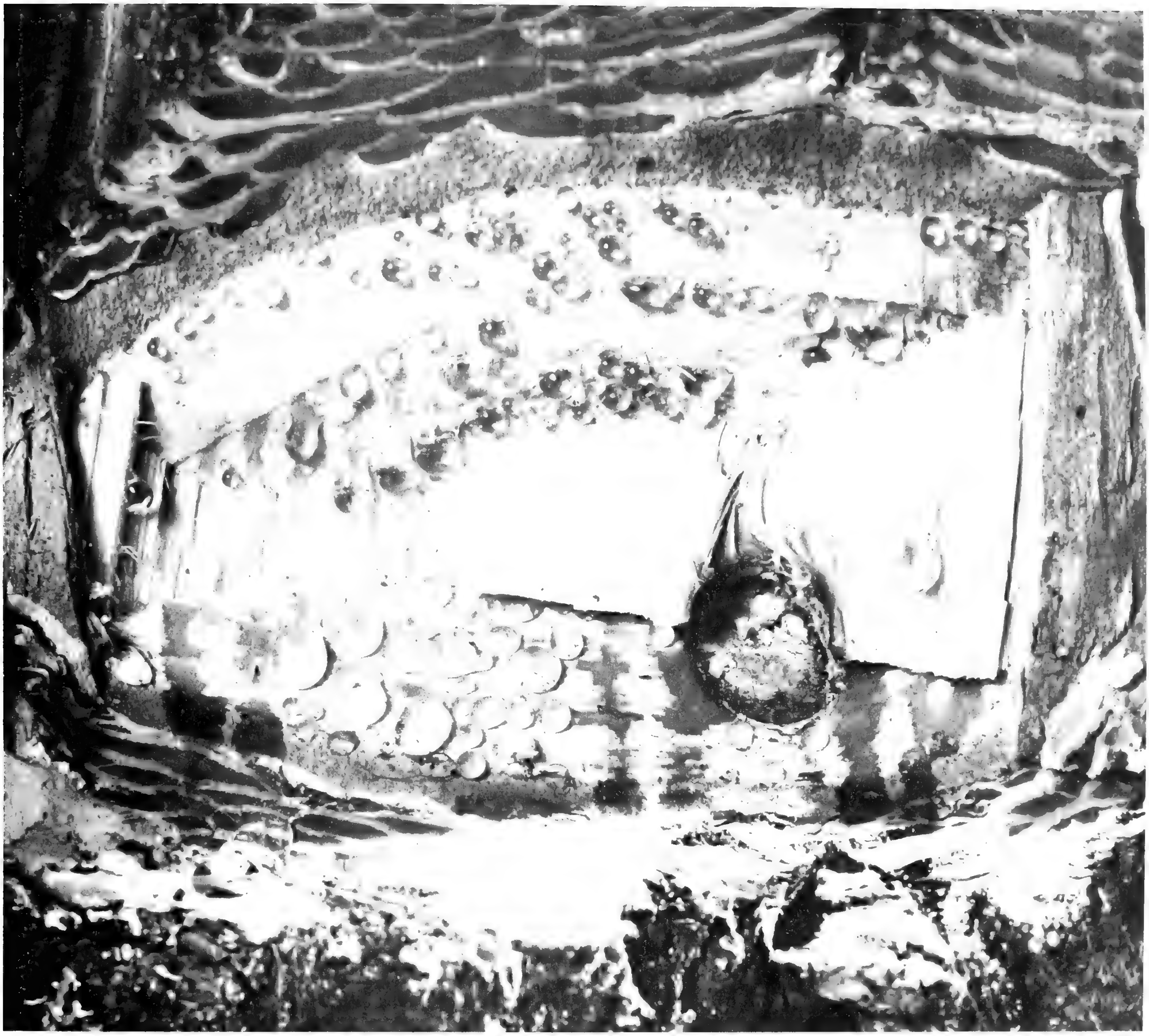

Figure 4.--Production of resin in codominant tree (A) 3 hours and (B) 3 days after chopping, and (C) absence of resin flow after 3 days in suppressed tree in same stand. Flathead National Forest, Montana.

Figure 5.--Mature Douglas-fir stand in grand fir-pachistima habitat type, Clearwater River drainage, Idaho. High density combined with a preponderance of Douglas-fir approximately 90 years old or older combine to make such stands highly susceptible.

felled stems and attack less densely the lower boles of standing trees (Furniss 1962). After dense stands are cut, greater illumination and higher temperatures of stems discourage beetles from arresting there. This behavior of DFB, coupled with less moisture stress in residual trees in cutover stands, seems to account for the turnabout in susceptibility of those stands.

Species Diversity and Habitat Type

Mortality groups invariably contain more DF than other tree species. Thus, species diversity is a factor in susceptibility to DFB.

In drainages like the Clearwater River, DF often grows in dense communities that are rather homogeneous in age and species, particularly in grand fir and cedar habitat types. However, Douglas-fir is a wide-ranging species adapted to diverse environments. In northern and central Idaho, DF is recognized as a climax or major seral species in 40 habitat types (Daubenmire and Daubenmire 1968, Steele et al. 1976, Steele et al. 1975). No systematic attempt has been made to rank habitat types by DFB hazard, but some impressions have been gained (R.A. Ryker, USDA Forest Service, Boise, Idaho, personal communication).

For example, two DF habitat types that are not associated with excessive DF damage are *Pseudotsuga menziesii/Carex geyeri-Artemisia tridentata* and *P. menziesii/C. geyeri-Symphoricarpos oreophilus*. The former is capable of supporting only 80 percent normal stocking--barely the threshold density of mortality groups that we have inventoried in more susceptible habitat types, such as grand fir/pachistima and western redcedar/pachistima. Similarly, the *P. menziesii/C. geyeri-S. oreophilus* habitat type tends not to support closed stands because presence of *C. geyeri* often restricts regeneration of trees.

Frequently, DF habitat types of the series *Spirea betulifolia*, *Physocarpus malvaceus*, and *Symphoricarpos albus* contain stands with a good mixture of ponderosa pine. This mixture restricts DFB mortality to dense, older groups of DF of limited area, particularly during droughty years. Although DF occurs in northern and central Idaho as a major seral species in 10 subalpine fir habitat types, major DFB outbreaks have not occurred there, possibly because of their colder climate.

Tree Age

The average age of hundreds of DFB-killed trees that we have examined exceeds 120 years. Age of attacked trees varies with locality and population pressure, however. During a recent outbreak in the Clearwater River drainage, some very dense stands containing trees 80 years old or less were attacked. Such young trees seldom die from attack, however.

In an earlier study, attractant pheromone was applied to 18 younger (80 years) and 32 older (170 years) trees on the Boise National Forest, Idaho (Furniss et al. 1972). None of the younger trees was killed, whereas 41 percent of the mature trees were successfully attacked. Likewise, 6 of 13 (46 percent) 133-year-old frontalin-baited trees were attacked successfully in the Clearwater drainage (Ringold et al. 1965).

Diseases

Dwarf Mistletoe

We have not observed a correlation between Douglas-fir dwarf mistletoe, *Arceuthobium douglasii* Engelmann, and DFB susceptibility in Idaho. A similar situation exists with lodgepole pine and *A. americanum* (Nuttall), presumably because infected trees have thinner bark (McGregor 1978).

We speculate that severe infection of DF by *A. douglasii* may result in reduced resin production (Weir 1916), making the affected tree less attractive to DFB. In any case, we have not seen any preferential association of DFB with dwarf mistletoe-infected DF; and we have noted poor brood production and spindly larval mines in DF afflicted with very severe mistletoe infection.

However, a possible relationship between *A. douglasii* and DFB has been reported in the Northwest (Weir 1916) and the southern Rocky Mountains (Stevens and Hawksworth 1970). To resolve the question, ratios of frequency of DFB infestation in the two categories of host trees need to be determined. We will report such information for stands in the Clearwater River and Boise River drainages when fieldwork is completed.

Root Diseases

A tie seems to exist between DFB and root diseases, but the firmness of the knot is hard to measure. Trees infected with root diseases often lack disease symptoms (Partridge and Miller 1972). Excavating the root system of a mature DF is a formidable job but is expedited by detonating explosive charges around the roots of felled trees (Miller and Partridge 1973) (fig. 6). Even so, it is feasible to examine only relatively little of the root

system if many trees are involved. Then, too, we wonder if incipient root disease may not develop more rapidly when the host tree dies. That would introduce a bias relative to uninfested trees that contained similar incipient infections.

Figure 6.--Preparation for blasting to excavate dirt from around roots to aid in examination for root rot infection.

Nonetheless, some evidence of an association of root disease and susceptibility to DFB has been developed (Furniss et al. 1979b). In that exploratory study, four trees were selected from each of two infested groups. Each set of trees represented the following conditions: susceptible (readily killed), intermediate (some larval mines present, but resinosis evident), resistant (no larval mines, trees survived), and not attacked. Amount of root disease was generally correlated with success of DFB attack. *Armillaria mellea* (Vahl. ex Fr.) Quel was the most frequently observed pathogen. Three trees with roots 70 to 90 percent killed were successfully invaded by beetles. Two with 30 to 40 percent of their roots killed had mostly unsuccessful attacks, and one tree with no visible diseased roots had no attacks. These trees were about 100 years old, growing in a grand fir-pachistima habitat type and in well-developed, fertile soil.

Onset of root disease in mature trees probably contributes to their susceptibility by increasing moisture stress (Vité and Rudinsky 1962), but we have examined too many infested DF that had no evident symptoms to believe that root disease is obligatory. Rather, we view susceptibility as the product of complex relationships involving numerous factors, important among which is root disease.

Injuries

Fire

Mainly because of the 1933 Tillamook fire in Oregon, fire injury has been inferred to be an important DFB susceptibility factor. After that exceptionally large fire, 200 million board feet of green DF were killed by beetles that had bred in fire-injured trees (R. L. Furniss 1941). However, no similar DFB outbreak associated with fire has been recorded in literature.

In a smaller fire, heat injury made a majority of trees susceptible to DFB attack (increasing with tree diameter and severity of injury short of death), but attack density, success, and infested height were low (Furniss 1965). We speculate that odors emitted from fire-injured trees are a source of attraction to beetles. Larger trees may be more attractive visually as well as in amount of odor. Whatever the case, many fire-injured trees retained sufficient resistance to survive. The DFB population was unable to expand and infest green trees surrounding the fire.

Wind and Snow

Windthrow caused by intense windstorms is fairly common in coastal areas and in the Northern Rocky Mountains where trees are large. By contrast, trees in the Southern Rocky Mountains are often shorter and grow on rockier soil; so they are more windfirm. Windfelled trees are attractive to DFB, more so if they are recently felled, large, and shaded (McMullen and Atkins 1962, Furniss 1962).

Accumulation of moist, heavy snow sometimes breaks the tops out of trees and subjects them to DFB infestation. Attracted beetles spill over into surrounding trees, creating typical mortality groups. This susceptibility factor is poorly publicized, and we rate it important in the Clearwater River drainages in northern Idaho. Classification of susceptibility in that area should provide for possible sudden increase in DFB infestation as a result of storm damage. Areas of storm hazard might be mapped with aid of a meterologist, although we have not explored that possibility.

Defoliation

Much like the case of mistletoe infection, insect-caused defoliation of DF has been linked circumstantially with DFB susceptibility. Recently such a link was reported for Douglas-fir tussock moth (Berryman and Wright 1978). Although proportional occurrence of DFB mortality in defoliated and undefoliated trees was not reported, defoliation was shown to result in increased brood production and increased rate of tree mortality. A less well documented relationship between DF defoliated by western spruce budworm and

DFB susceptibility has been reported periodically in annual forest insect survey reports of the USDA Forest Service and the Canadian Forestry Service.

Verbal Model

The following verbal model (Furniss et al. 1979) is proposed to explain the functioning of factors affecting DF abundance and susceptibility of host trees.

Disturbances (e.g., windstorms and, to a lesser extent, fire) contribute to increased DFB populations. When such disturbances cease, beetles seek out and attack live trees; their success depends upon the susceptibility of the attacked trees. The proportion of Douglas-fir in a stand, and stand density and age are positively correlated with susceptibility. Any of those factors can limit DFB damage. Trees broken by weight of snow, stressed by drought, infected with root rots, or possibly defoliated by tussock moths are susceptible and may contribute to furtherance of the outbreak.

As susceptible trees are killed by beetles, stand density is relieved by logging, or as environmental conditions improve (favoring growth and water relations), resistance to population expansion mounts.

Size of infested groups declines and a higher proportion of attacked trees may survive. Numbers of natural enemies appear to be independent of prey density; influence of enemies increases after the bark beetle population subsides. Populations are maintained at an endemic level primarily by tree resistance and natural enemies.

ACQUISITION OF DATA

The following procedures were developed in the Clearwater River drainage. They are being applied to additional areas in that drainage and in the Boise River drainage where the rate of DFB infestation has been above normal in recent years.

Selection of Stands

We are concentrating our attention in areas where extensive unmanaged stands are available. The fact that cutover stands have no DFB damage to sample should not be passed over lightly by the reader.

Two steps are involved:

Step 1--We examined Idaho insect survey reports for general location of DFB mortality. Mortality as old as 3 years is satisfactory for sampling. Then we obtained detailed aerial survey maps for the areas of interest from the agencies that conducted the damage surveys. Shown on those maps are the approximate locations and size of groups of DF having symptomatic reddened foliage.

Step 2--We observed candidate areas from aircraft to confirm their suitability for sampling and to obtain oblique stereo 35-mm color slides (Walsh and Hall 1978). The general area was photographed, slightly overlapping the sides of subsequent photo pairs. The center of interest of each photo pair was a lateral ridge or a drainage. The bottom and top of each photo spanned the width of the area to be sampled. For example, we exposed 24 stereo pairs to photograph a 16 × 2 mi (26 × 3.2 km) zone bordering the Selway River. The aircraft flew above the river at 6,300 ft (1,920 m) elevation; the landscape varied from 1,600 ft (488 m) at the river to 5,600 ft (1,707 m) at the top of the slope. That is steep country, characteristic of many areas where DF grows, and is one reason why the saw has not yet found the stands where the DFB has caught our attention.

Then we flew back over the same course at 5,300 ft (1,615 m) elevation and selectively photographed areas of intense damage at larger scale. The smaller scale oblique stereo photos were taken to orient the larger scale photos and to aid crews in traveling to groups that they couldn't see on the ground; the larger scale photos were used to select locations of sample plots in mortality groups and green stands.

Field Sampling

We had hoped to sample areas where stands had been delineated and inventoried by the managing agency. That would have provided us existing data on green stands, including the area encompassed by each sampled stand with which to weight the variable radius plot data (Daniels et al. 1979). However, such information was not available in areas of DFB mortality that we wished to sample.

Crew Organization

Crews consisted of three persons each. They were provided planimetric maps of 1/2 inch = 1 mi (1.26 cm = 1.61 km) scale for general orientation; U.S. Geological Survey 7-1/2 min quadrangle maps (1:24,000 scale) with 40-ft (12-m) contours and approximate locations of groups and plots, and route of travel; oblique stereo 35-mm color slides of the day's work area; and

1:14,840 scale vertical stereophotos (for orientation). Wherever possible, crews were transported-sometimes by helicopter--to a starting point at high elevation where they worked their way down ridges to the sample plots. Often they had to be transported by raft across rivers, such as the Selway, at the conclusion of the day's sampling.

Duties of the three crewmembers were as follows, although shifting of assignments was permitted.

(1) Locate and establish plots; operate Relascope[3]; determine aspect, slope, topographic position; determine height of tallest DF; determine habitat type; describe soil.

(2) Record data; determine crown class, crown ratio; observe mistletoe and crown ailments, including defoliation; help with increment boring.

(3) Paint numbers on trees; measure d.b.h. of plot trees; determine species of plot trees; observe root rot and stem diseases; bore tallest DF for age, 10-year growth of largest and smallest trees of each species.

Variable radius plots (40-factor prism) were located approximately 50 m apart either within mortality groups or in stands free of mortality. Green stand plots were laid across (not along) contours. Each crew established 8 to 12 plots per day equally divided between mortality groups and green stands.

Variables Sampled

Variables sampled (or constructed from sample data) are shown in table 2. Descriptors were grouped as follows: tree related, stand related, or site or physiographic. The detail with which any factor could be examined and measured was limited to that which was possible while keeping time per plot well within 1 hour. Such exploratory effort was believed to be sufficient to capture significantly correlated relationships of a major sort. Later we may study some relationships in more detail, but the level of refinement will depend upon interest and need expressed by agencies involved with protection and management of the forest resource.

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[3] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others which may be suitable.

Most of the descriptors sampled are included commonly in stand inventories and other susceptibility studies. However, some explanation of our methodology involving soil, diseases, and habitat type may be helpful.

Soil was examined to a depth of approximately 40 in (1 m) by digging with a tile spade to 18 in (46 cm), then with an auger 3.25 in (8.3 cm) in diameter. We recorded depth of *A* horizon, depth at which rocks were encountered if present, depth to *C* horizon, texture (hard, soft) of surface of *C* horizon, and depth of volcanic ash if present.

Tree diseases were identified symptomatically (Partridge 1974) and recorded as present or absent except for dwarf mistletoe, which was rated according to the method proposed by Hawksworth (1977). Time permitted chopping into root crowns only if external symptoms were visible.

Habitat type was determined for plots in the main Clearwater River drainage using Daubenmire and Daubenmire (1968). For the Selway River and Boise River drainages, we referred to Steele et al. (1975, 1976). Whenever vegetation on plots indicated that succession had been affected by relatively recent disturbance (fire, grazing), adjacent, less disturbed areas were observed to arrive at a classification.

ANALYSES OF DATA

Plot data were analyzed by the SCREEN computer program (Hamilton and Wendt 1975) to determine independent variables correlated with either presence or absence of mortality. Then, correlated variables were analyzed by the RISK computer program (Hamilton 1974, Hamilton and Edwards 1976) to obtain probabilities of mortality for combinations of descriptors.

The SCREEN program readily accommodates a large number of independent variables (mortality or green stand). Each variable can be divided into eight or fewer classes that need not be equal in size. Care is needed in setting class intervals for variables that may be clumped, otherwise significant relationships may be masked. Setting intervals is best accomplished by listing or plotting frequencies of values in order to identify natural class limits.

The RISK program computes a numerical value from 0 to 1--proportional to the degree of risk of mortality--for any combination of significant variables. This procedure provides a convenient means of stratifying stands by degree of risk of DFB mortality.

Table 2.--Variables measured to correlate with presence or absence of Douglas-fir beetle mortality

Tree Descriptors
Species
d.b.h.
Crown ratio
Crown class including broken top
10-yr growth
Height
Age
Infestation class (not infested, successful, unsuccessful)
Mistletoe
Root disease
Stand and Site
Mortality present or absent
Habitat type
Elevation
Aspect
Slope
Topographic position
Proportion of Douglas-fir
Basal area, total
Basal area, Douglas-fir
Crown competition factor
Disturbances (nearby root disease center, windfall, snowbreak)
Soil (A horizon, depth to C, quality of surface of C., rocks present or absent, depth of volcanic ash)
Area of mortality or green stand (and number of samples)
Number of dead trees per group

Example

The described methodology was tested in 1977 in Shattuck Creek drainage, Latah County, Idaho. The study area consisted of a dense, mature second-growth forest of the cedar-pachistima and grand fir-pachistima habitat types. Areas occupied by DF mortality and stands free of mortality were determined during sampling and from reference to aerial photos and topographic maps. For comparison, we computed risk with and without weighting the plots by estimates of the areas they represented. Daniels et al. (1979) describe similar procedures. Like their published example, ours is intended only to illustrate. We plan a more vigorous presentation when fieldwork is completed. That work is taking more detailed account of a wider range of variables, including proportion of DF, stand age, stand density, soil, diseases, and habitat types.

In our example-which involved a rather homogeneous area without a wide range of density, age, and tree species--the SCREEN program identified the most prevalent crown class as being significantly correlated ($p = 0.05$) with occurrence of mortality. Habitat type and slope were only significant at the 0.50 level of probability but are included for sake of demonstration. Table 3 contains test probabilities for combinations of those variables using unweighted and weighted samples. The most susceptible stands had a high proportion of more dominant trees and occurred on steeper slopes in the cedar-pachistima habitat type.

The importance of weighting samples by the inverse of the sampling intensity is readily apparent from the reduction of probabilities and changes in rankings. Even a rough estimate of areas of mortality and green stands is better than assuming that they are equal.

CONCLUSIONS

Factors underlying DFB susceptibility have been discussed and incorporated into a verbal model explaining changes in DFB populations and DF mortality. Understanding the way those factors function is prerequisite to developing a versatile stand susceptibility classification.

Three universally present factors--stand density, stand age, and proportion of DF--are directly correlated with mortality. Each of those factors can limit mortality. For example, a dense stand of young DF (less than 80 years) is not susceptible to killing by DFB. Simplistically, the potential for DFB damage could be determined by summing numerical "penalties" for those three variables in a manner similar to that suggested for spruce beetle (Schmid and Frye 1976).

Table 3.--Probability of occurrence of Douglas-fir beetle in stands having selected combinations of prevailing crown class, habitat type, and slope

Significant independent variable[1]			Probability of mortality[3]	
Prevailing crown class (CC)	Habitat type (HT)	Slope (S)	Not weighted[2]	Weighted
1	1	20	0.60	0.14
2	1	20	.52	.03
3	1	20	.44	.01
4	1	20	.36	.01
1	2	20	.84	.42
2	2	20	.79	.12
3	2	20	.73	.03
4	2	20	.67	.01
1	1	10	.65	.08
1	2	10	.87	.28
1	1	30	.56	.23
1	2	30	.82	.57
3	1	10	.49	.01
3	2	10	.77	.01
3	1	30	.39	.01
3	2	30	.70	.05

[1] The independent variables were: crown class (1 = dominant, 2 = codominant, 3 = intermediate, 4 = suppressed); habitat type: (1 = grand fir-pachistima, 2 = cedar-pachistima); slope is in degrees.

[2] Data from mortality and green stands were weighted by the inverse of their sampling intensities. Weight for mortality data was 24 acres/31 plots = 0.77; weight for green stand data was 380 acres/69 plots = 5.51.

[3] Regression coefficients for mortality model were (not weighted, weighted): prevailing crown class (-0.330072, -1.64255), habitat type (1.26117, 1.50144), slope (-0.0192382, 0.0608783), constant (1.3294, -1.41611).

$$p = 1 + e^{-(\beta_0 + \beta_1 CC + \beta_2 HT + \beta_3 S)}\ {}^{-1}$$

However, additional factors, some subject to chance, are implicated in the probatility of occurrence of DFB damage. Methods by which these diverse factors are being sampled and analyzed have been presented. Care is being taken to obtain data in a manner compatible with that used by resource agencies in Idaho to assure acceptance and applicability of the method. When this work is completed, the method of classifying DFB susceptibility by application of the logistic function to stand and site variables correlated with mortality should help protection specialists and resource managers to better identify the stands most in need of treatment to prevent mortality caused by the Douglas-fir beetle.

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LITERATURE CITED

Belluschi, P. G., N. E. Johnson, and H. J. Heikkenen. 1965. Douglas-fir defects caused by the Douglas-fir beetle. J. For. 63:252-256.

Berryman, A. A., and L. C. Wright. 1978. Defoliation, tree condition, and bark beetles. p. 81-87. *In* The Douglas-fir tussock moth: a synthesis. M. H. Brookes, R. W. Stark, and R. W. Campbell, eds. U.S. Dep. Agric. For. Serv. and Sci. Educ. Agency, Tech. Bull 1583.

Daniels, R. F., W. A. Leuschner, S. J. Zarnoch, H. E. Burkhart, and R. R.

Hicks. 1979. A method for estimating the probability of southern pine beetle outbreaks. For. Sci. 25:265-269.

Daubenmire, R., and J. B. Daubenmire. 1968. Forest vegetation of eastern Washington and northern Idaho. 104 p. Washington Agric. Exp. Stn., Tech. Bull. 60.

Furniss, M. M. 1962. Infestation patterns of Douglas-fir beetle in standing and windthrown trees in southern Idaho. J. Econ. Entomol. 55:486-491.

Furniss, M. M. 1975. Susceptibility of fire-injured Douglas-fir to bark beetle attack in southern Idaho. J. For. 63:8-11.

Furniss, M. M. 1976. Controlled breeding, comparative anatomy and bionomics of *Dendroctonus simplex* LeConte and *Dendroctonus pseudotsugae* Hopkins (Coleoptera:Scolytidae). p. 109-210. *In* Anniversary publication, University of Idaho, Dep. Entomol. W. F. Barr, ed.

Furniss, M. M. 1979. An annotated bibliography of the Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins). 40 p. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. INT-48. Intermount. For. Range Exp. Stn., Ogden, Utah.

Furniss, M. M. 1981. Pruebas de cruzamiento entre poblaciones de *Dendroctonus pseudotsugae* Hopk. procedentes de Chihuahua, Mex. e Idaho EUA. Folia Entomológica Mexicana. [In press.]

Furniss, M. M., L. N. Kline, R. F. Schmitz, and J. A. Rudinsky. 1972. Tests of three pheromones to induce or disrupt aggregation of Douglas-fir beetles in live trees. Ann. Entomol. Soc. Am. 65:1227-1232.

Furniss, M. M., M. D. McGregor, M. W. Foiles, and A. D. Partridge. 1979. Chronology and characteristics of a Douglas-fir beetle outbreak in northern Idaho. 19 p. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. INT-59. Intermount. For. Range Exp. Stn., Ogden, Utah.

Furniss, M. M., and P. W. Orr. 1978. Douglas-fir beetle. 4 p. U.S. Dep. Agric. For. Serv., Insect and Disease Leafl. 5, rev. Washington, D.C.

Furniss, M. M., and R. F. Schmitz. 1971. Comparative attraction of Douglas-fir beetles to frontalin and tree volatiles. 16 p. U.S. Dep. Agric. For. Serv., Res. Pap. INT-96. Intermount. For. Range Exp. Stn., Ogden, Utah.

Furniss, R. L. 1941. Fire and insects in the Douglas-fir region. Fire Control Notes 5:211-213. U.S. Dep. Agric. For. Serv., Washington, D.C.

Hamilton, D. A., Jr. 1974. Event probabilities estimated by regression. 8 p. U.S. Dep. Agric. For. Serv., Res. Pap. INT-152. Intermount. For. Range Exp. Stn., Ogden, Utah.

Hamilton, D. A., Jr., and B. M. Edwards. 1976. Modeling the probability of individual tree mortality. 22 p. U.S. Dep. Agric. For. Serv., Res. Pap. INT-185. Intermount. For. Range Exp. Stn., Ogden, Utah.

Hamilton, D. A., Jr., and D.L.R. Wendt. 1975. SCREEN: a computer program to identify predictors of dichotomous dependent variables. 20 p. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. INT-22. Intermount. For. Range Exp. Stn., Ogden, Utah.

Hanover, J. W., and M. M. Furniss. 1966. Monoterpene concentration in Douglas-fir in relation to attack by the Douglas-fir beetle. p. 23-28. *In* Second genetics workshop: joint proceedings, Society of American Foresters and Seventh Lake States Forest and Tree Improvement Conference. [Hickory Corners, Mich., Oct. 1975.] U.S. Dep. Agric. For. Serv., Res. Pap. NC-6. North Central For. Exp. Stn., St. Paul, Minn.

Harrington, T. C., M. M. Furniss, and C. G. Shaw. 1981. Dissemination of Hymenomycetes by *Dendroctonus pseudotsugae* (Coleoptera:Scolytidae). Phytopathol. [In press.]

Hawksworth, F. G. 1977. The 6-class dwarf mistletoe rating system. 7 p. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. RM-48. Rocky Mount. For. Range Exp. Stn., Fort Collins, Colo.

Hopkins, A. D. 1921. Contributions toward a monograph of the scolytid beetles. I. The genus *Dendroctonus*. 1909. p. 1-164. II. Preliminary classification of the super-family Scolytoidea. 1915. U.S. Dep. Agric., Bur. Entomol. Tech. Ser. 17, p. 165-247.

Little, E. L., Jr. 1979. Checklist of United States trees (native and naturalized). 375 p. U.S. Dep. Agric. For. Serv., Agric. Handb. 541. Washington, D.C.

McGregor, M. D. 1978. Management of mountain pine beetle in lodgepole pine stands in the Rocky Mountain area. *In* Proceedings of a symposium on theory and practice of mountain

pine beetle management in lodgepole pine forests. 224 p. [Moscow, Idaho, Apr. 1978.] Univ. Idaho, Moscow.

McMullen, L. H., and M. D. Atkins. 1962. On the flight and host selection of the Douglas-fir beetle, *Dendroctonus pseudotsugae* hopk. (Coleoptera:Scolytidae). Can. Entomol. 94:1309-1325.

Miller, D. L., and A. D. Partridge. 1973. Fungus associations in root rots of grand fir. Plant Dis. Rep. 57:346-348.

Partridge, A. D. 1974. Major wood decays in the Inland Northwest. 125 p. Idaho Res. Found. Nat. Res. Ser. 3, University of Idaho, Moscow.

Partridge, A. D., and D. L. Miller. 1972. Bark beetles and root rots related in Idaho conifers. Plant Dis. Rep. 56: 498-500.

Pitman, G. B., R. L. Hedden, and R. I. Gara. 1975. Synergistic effects of ethyl alcohol on the aggregation of *Dendroctonus pseudotsugae* (Col., Scolytidae) in response to pheromones. Z. Angew. Entomol. 78:203-208.

Pitman, G. B., and J. P. Vité. 1970. Field response of *Dendroctonus pseutotsugae* (Coleoptera:Scolytidae) to synthetic frontalin. Ann. Entomol. Soc. Am. 63:661-664.

Ringold, G. B., P. J. Gravelle, D. Miller, M. M. Furniss, and M. D. McGregor. 1975. Characteristics of Douglas-fir beetle infestation in northern Idaho resulting from treatment with Douglure. 10 p. U.S. Dep. Agric. For. Serv., Res. Note INT-189. Intermount. For Range Exp. Stn., Ogden, Utah.

Rudinsky, J. A. 1962. Ecology of Scolytidae. Ann. Rev. Entomol. 7:327-348.

Rudinsky, J. A. 1966. Host selection and invasion by the Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins, in coastal Douglas-fir forests. Can. Entomol. 98:98-111.

Rudinsky, J. A., and L. C. Ryker. 1976. Olfactory and auditory signals mediating behavioral patterns of bark beetles. p. 195-209. *In* Coll. Int. CNRS No. 265--Comportement des Insectes et Milieu Trophique. [Tours, France, Sept. 1976.]

Rumbold, C. T. 1936. Three blue-staining fungi, including two new species, associated with bark beetles. J. Agric. Res. 52:419-437.

Schmid, J. M., and R. H. Frye. 1976. Stand ratings for spruce beetles. 4 p. U.S. Dep. Agric. For. Serv., Res. Note RM-309. Rocky Mount. For. Range Exp. Stn., Fort Collins, Colo.

Stairs, G. R. 1968. Monoterpene content in *Larix*. Silvae Genet. 17:182-186.

Steele, R., S. F. Arno, and R. D. Pfister. 1976. Preliminary habitat types of the Nez Perce National Forest. 71 p. U.S. Dep. Agric. For. Serv., Intermount. For. Range Exp. Stn., Ogden, Utah. [Processed.]

Steele, R., R. D. Pfister, R. A. Ryker, and J. A. Kittams. 1975. Forest habitat types of central Idaho. 191 p. U.S. Dep. Agric. For. Serv., Intermount. For. Range Exp. Stn., Ogden, Utah. [Processed.]

Stevens, R. E., and F. G. Hawksworth. 1970. Insects and mites associated with dwarf mistletoes. 12 p. U.S. Dep. Agric. For. Serv., Res. Pap. RM-59. Rocky Mount. For. Range Exp. Stn., Fort Collines, Colo.

Vité, J. P., and J. A. Rudinsky. 1962. Investigations on the resistance of conifers to bark beetle infestation. XI Int. Congr. Entomol., Vienna 1960. Sonderdr. Verh. II:219-225.

Walsh, T. H., and W. B. Hall. 1978. Pocket guide for making color oblique stereo aerial (COSA) photographs with 35 mm cameras. 10 p. Geophotography and Remote Sensing Center, University of Idaho, Moscow.

Weir, J. R. 1916. Mistletoe injury to conifers in the Northwest. 39 p. U.S. Dep. Agric. Bur. Plant Ind., Bull. 360. Washington, D.C.

APPLICATION OF MODELS DEVELOPED TO RISK RATE FOREST SITES AND STANDS TO DOUGLAS-FIR TUSSOCK MOTH DEFOLIATIONS[1]

Peter G. Mika, Robert C. Heller, and Karel J. Stoszek[2]

In 1973 a Douglasfir tussock moth (DFTM) outbreak was in full swing in the Pacific Northwest. Partly in response to this, the Federal Government appropriated funds for a short-term research program aimed at reducing damage caused by this pest, these funds giving rise to the USDA Expanded Douglasfir Tussock Moth Research and Development Program. Under the auspices of this program, two studies aimed at developing risk-rating systems for the DFTM were initiated by researchers at the University of Idaho. One study, directed by Robert Heller, worked with aerial photography of the tussock moth outbreak in the Blue Mountains of northeastern Oregon and southeastern Washington and the other, led by Karel Stoszek, utilized data collected on the ground from an outbreak in the Palouse Range of northern Idaho. In this paper we describe the results of these two studies and a case study implementation of those results and discuss some implications for pest and forest management.

THE INSECT

The DFTM, *Orgyia pseudotsugata* (McD.), is a defoliating insect capable of causing severe damage and mortality in conifers in the western United States and Canada. The insect has three primary hosts--the mountain variety of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), grand fir (*Abies grandis* [Dougl.] Lindl.), and white fir (*Abies concolor* [Gord. & Glend.] Lindl.)--and is found throughout the ranges of these tree species (Beckwith 1978).

The insect has one generation a year. The female lays her eggs on her own cocoon in early fall, and hatch occurs in late spring. Development rates are strongly influenced by accumulation of heat units; thus eclosion is well synchronized with bud burst of the host. Larvae go through five to seven instars: first and second instars require new foliage to survive, but more mature instars are able to successfully feed on older needles. Pupation occurs in late summer and adults emerge in early fall (Wickman and Beckwith 1978).

The adult female is wingless; thus wind movement of first and second instars accounts for almost all of the dispersal. While longdistance dispersal does occur, seldom are sufficient concentrations of larvae reached to initiate new outbreaks. For this reason, outbreaks are believed to develop in place (Mason and Luck 1978).

Outbreaks are of short duration, generally lasting 3 to 4 years, and follow a consistent pattern. This pattern can be broken into four phases (fig. 1): a period of release, when insect numbers rapidly increase to levels resulting in visible tree defoliation; a peak phase, in which maximum insect densities are reached; a period of rapid decline in insect numbers due to reduced food availability and increased effects of natural enemies and disease; and a postdecline phase in which collapse of the insect population is completed. Insect numbers may show enormous fluctuations, increasing by a factor of 10,000 to 100,000 during the outbreak (Mason and Luck 1978).

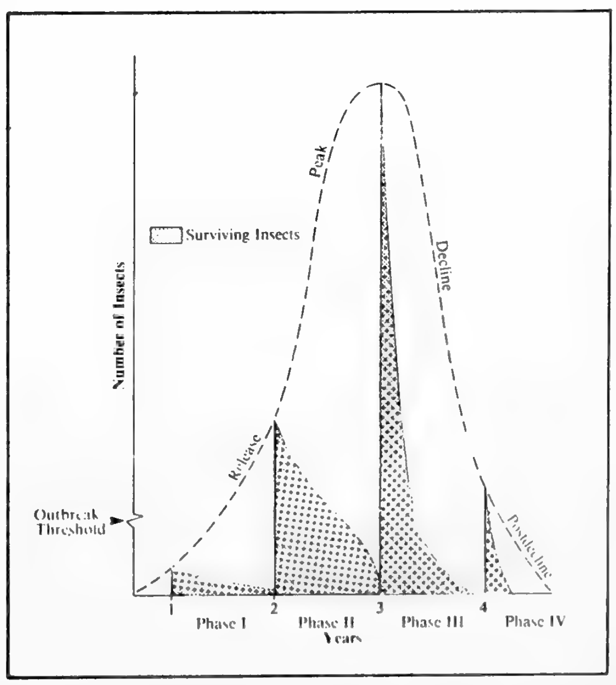

Figure 1.--Schematic representation of a tussock moth outbreak (from Mason and Luck 1978).

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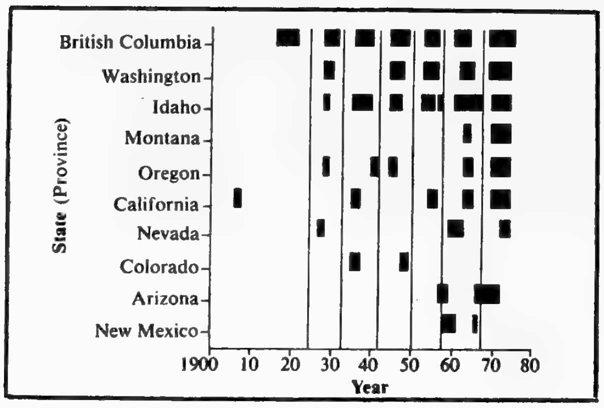

Figure 2.--Occurrence of Douglas-fir tussock moth outbreaks by State and Province (from Clendenen 1975[3]).

In general, outbreaks are synchronized over large areas (fig. 2), implying that weather phenomena may have an important bearing on outbreak development. Studies have found associations of outbreaks with above-average spring temperatures and below-average August precipitation,[3] and with one or more preceding years of below-normal precipitation (Wickman 1963, Lessard 1974). There is also some evidence that outbreaks are cyclic, recurring at 8- to 10-year intervals (Sudgen 1957, Tunnock 1973).

Under outbreak conditions the tussock moth is capable of severely damaging the forest resource through direct and indirect tree mortality, top kill, and growth reduction. For example, in the recent outbreak in the Blue Mountains of northeastern Oregon, heavy defoliation resulted in about 40 percent mortality and 40 percent top kill. For trees defoliated 50 percent or more, radial growth was reduced by 58 percent (Wickman 1978a).

THE RISK-RATING MODELS

To have effective forest or pest management, we need the ability to predict spatial and temporal changes in pest populations and resulting damage to the forest resource. The manager must be able to forecast where, when, and to what extent a particular pest will cause damage. We feel that development of risk-rating systems based on site and stand characteristics is the first step toward attaining these capabilities. Such systems can be directly utilized to identify high-hazard areas for location of early detection, monitoring, and potential control efforts. Also, when linked to a forest growth projection system, risk-rating systems can provide a tool for predicting future resource losses and evaluating alternative management strategies. Finally, although such systems are usually based on empirical correlations, the relationships between levels of pest damage and characteristics of sites and stands give us some clues as to what conditions cause the pest problem to develop. Based on this, we then have some rationale on which to develop forest and pest management strategies to reduce or prevent future problems.

With these thoughts in mind, we initiated two studies aimed at developing risk-rating systems for DFTM defoliation, one study using information obtained from aerial photographs and the other based on data collected on the ground. We hoped to end up with risk-rating models with good predictive ability; however, other criteria were also important in development of the models. First, we felt that the information required to apply any risk-rating model should be available from standard resource inventories. Second, the variables used to predict the defoliation risk should represent factors that a manager could alter through silvicultural treatment. And finally, the models should be compatible with current stand projection techniques and thus allow the manager to explore the consequences of alternative pest management strategies.

The Blue Mountains Study

This study[4] was conducted in the Blue Mountains of northeastern Oregon and southeastern Washington. In 1973 the USDA Forest Service took color infrared 1:4,000 aerial photographs on 16 randomly located, 6-mile flight lines. Clusters of three 1-acre plots were systemstically laid out on the photography, each cluster located at a 20-chain interval from the previous cluster. In all, 712 plots on 12 flight lines were selected for further analysis. Using standard photo interpretation techniques (Heller and Sader 1980), we extracted data on the structure and position of each plot. Data included percent slope, aspect, physiographic location (ridgetop, sidehill or bottom), crown closure (open or closed), canopy structure (onestoried or multistoried), average crown diameter, percent cover by all tree species, and percent cover by host species (Douglas-fir and grand fir). Elevation was determined by examining contour maps of the area.

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[3] From a preliminary report by G. Clendenen, 1975. Tussock moth, *Orgyia pseudotsugata* (McD.), outbreaks and climatic factors: a correlation analysis. 60 p. USDA For. Serv. Coop. Aid Agreement. Coll. For. Res., Univ. Washington, Seattle.

[4] Unpublished report by R. C. Heller, S. A. Sader, and W. A. Miller. 1977. Identification of preferred Douglas-fir tussock moth sites by photo interpretation of stand, site and defoliation conditions. 23 p. Final Rep., USDA DFTM Res. Develop. Prog., Coll. Forestry, Wildlife and Range Sciences, Univ. Idaho, Moscow.

We calculated a defoliation index for each plot by taking a weighted average of the amount of defoliation on each host tree. Each host was classified into one of five categories: 0--no defoliation, 1--defoliation in the upper 1/3 of the crown, 2--defoliation in more than the upper 1/3 but less than the upper 2/3 of the crown, 3--defoliation in more than the upper 2/3 but less than the entire crown, and 4--defoliation of the entire crown. The classification of each tree was multiplied by its percent cover, summed over all host trees, and divided by the total percent cover in host trees to obtain the defoliation index.

Analysis was first attempted using multiple-regression techniques to relate the defoliation index of each plot to the plot's structure and position. However, no significant relationships could be established between defoliation and any of the various plot characteristics.

At that point each plot was classified as either defoliated or nondefoliated and fit to a logistic model involving the various measures of plot condition. The general model took the form

$$P = \frac{1}{1 + \mathrm{Exp}\,(-\Sigma\, B_i X_i)}$$

where P is the probability that defoliation has occurred, X is the value of the *i*th plot characteristic, and B_i is the *i*th regression coefficient. We used a nonlinear algorithm, RISK (Walker and Duncan 1967), to estimate the regression coefficients.

Using this latter technique, we developed a number of predictive models, each differing in the type of information needed as inputs to the model. The predictive ability of each model was evaluated with a χ^2 goodness-of-fit test; those models with the lowest χ^2 values represented the best fits of the data. Two models appeared to be most useful from the standpoint of application to forest management situations. The first of these (model I in table 1) makes use of information available from contour maps and standard 1:24,000 resource photography. Model II requires the same information as model I with the addition of data on the amount of cover in fir species. This latter information cannot be accurately determined on 1:24,000 photography but can be obtained from larger-scale photos or stand examination records.

Trends were consistent for all models examined. Probability of defoliation was higher in plots at low elevation, on ridgetops, with high tree density, with large crown trees, and with a high percentage of fir. The terms involving aspect can be combined into a single cosine function with a phase shift (Stage 1976); for Model I, highest defoliation probability occurred at 60 degrees while the phase shift for Model II occurred at 62 degrees.

The Palouse Range Study

This study, conducted in a tussock moth outbreak area within the Palouse Range north and east of Moscow, Idaho, was initiated in 1975 (Stoszek et al. 1981). The outbreak was first detected in 1972, but large-scale defoliation was not apparent until 1973. Most of the area was sprayed with DDT in 1974, thus arresting the outbreak in the release phase.

After preliminary stratification of the area by aspect, physiographic location, host species composition, and stand age, we selected 70 stands for detailed measurement. Data collected included site position (elevation, percent slope, aspect, physiographic location), site quality (habitat type, Douglas-fir site index), and soil characteristics (depth of volcanic ash mantle, rooting zone depth, bulk

Table 1.--Regression coefficients for probability of defoliation models

X_i	B_i Model I	B_i Model II
Intercept (X_i = 1)	-0.4320	-0.8529
Elevation (ft)	-0.0001185	-0.0002376
Slope (%)	+0.00284	-0.000522
Tan (Slope) × cos (Aspect)	+0.4536	+0.3481
Tan (Slope) × sin (Aspect)	+0.7794	+0.7338
Physiographic location	-0.2357	-0.3756
Total cover (%)	+0.0218	+0.0205
Average crown diameter (ft)	+0.0232	+0.0169
100 × Fir cover/Total cover		+0.0187

density). In each stand three variable-radius plots were established; trees in these plots were measured for d.b.h., height, crown length, age, and radial increment. We calculated estimates of individual tree foliage biomass using equations developed by Brown (1978) and overall stand estimates for density, diameter, age, and so forth using standard mensurational formulae.

Defoliation estimates were obtained through ocular ratings of six crown levels of dominant and codominant host trees (grand fir and Douglas-fir). Five defoliation categories were used: (1) none to < 5 percent, (2) 5 to 25 percent, (3) 26 to 50 percent, (4) 51 to 75 percent, and (5) 76 to 100 percent. We translated these individual crown level observations into proportion of foliage removed for the entire tree using regression estimators developed from detailed measurement of a destructively sampled subset of the visually rated trees. A simple average of all rated host trees served as the index of defoliation for each stand.

Defoliation was related to site and stand characteristics using multiple-regression techniques. In addition, due to a large number of highly correlated potential variables, we screened the variables using the ridge regression technique of Hoerl and Kennard (1970) in attempt to keep down prediction variance. The best model resulting from this procedure accounted for 53 percent of the variation. Independent variables included slope position (lower and upper), depth of volcanic ash, mean host age, percentage of total stand foliage biomass in grand fir

$$100 \times \frac{\text{grand fir foliage biomass}}{\text{stand foliage biomass}}$$

and an index of site occupancy

$$\frac{\text{foliage biomass per unit area}}{\text{Douglas-fir site index}}$$

Relationships between defoliation and characteristics of the site and stand are portrayed in figure 3; lines represent predicted values obtained from the model. Defoliation was heavier on upper slope sites, sites with poor productivity, and sites with little or no ash mantle. Defoliation increased as the average age of the host trees increased; young stands (less than 50 years old) showed little defoliation, regardless of other site and stand attributes. Defoliation also increased as the proportion of grand fir and the overall stand density increased.

Data were also analyzed in the same fashion as done in the Blue Mountains study; that is, stands were classified as defoliated or nondefoliated and resultant data were fit to a logistic model for predicting probability of defoliation. As in the previous study, a series of models was examined, each involving a different set of independent variables. The best data fit (lowest χ^2 value) was obtained with a model involving the same five variables identified in the standard regression analysis. However, we were able to obtain reasonable agreement between predicted and actual occurrence of defoliation using a three-variable model involving slope position, stand basal area per acre, and proportion of basal area in grand fir. Trends were identical to those found in the Blue Mountains study: defoliation was more likely to occur on ridgetop sites and in dense stands with a high proportion of grand fir.

APPLICATION OF THE MODELS

The models predicting probability of defoliation for both study areas have already been incorporated into the integrated DFTM model. This latter is actually a combination of three models: a stand-prognosis model that projects tree growth under normal conditions, a stand-outbreak model that combines a tussock moth population model and a tree damage model, and a socioeconomic model that provides economic evaluations of outbreak effects on timber, water, forage and wildlife, fire, and recreation (Colbert and Campbell 1978). In the structure of this overall system,

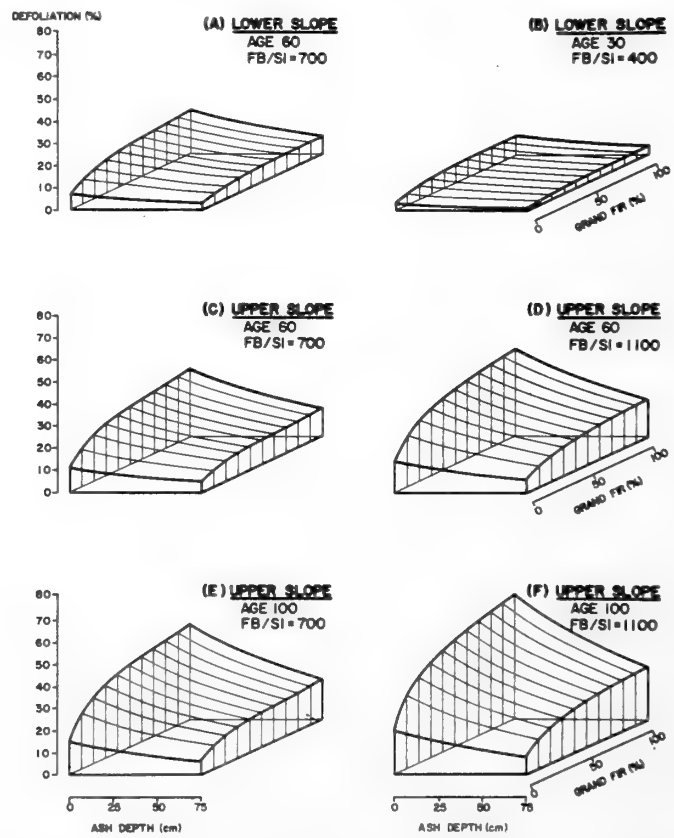

Figure 3.--Relationships between tussock moth defoliation and characteristics of site and stands in the Palouse Range study area.

the defoliation probability models function as switches, determining whether an outbreak will occur in a particular stand at a particular point in time (Stage 1978). Thus by allowing changes in stand characteristics resulting from stand growth, cultural treatments, or past tussock moth oubreaks to influence the likelihood of future outbreaks, these models provide for a dynamic interaction between the stand and the pest population within the projection system.

A more direct application of these risk-rating models is now being conducted at the University of Idaho. With funds provided by the USDA Forest Service, Region 1, FIDM State and Private, we have initiated a demonstration of the risk-rating models on a portion of the Palouse Ranger District of the Clearwater National Forest in northern Idaho.

As a first step, a series of new defoliation probability prediction models has been developed, combining variables found to be important in the Blue Mountain and Palouse Range studies. Calibration of these models used data from the 70 stands sampled in the Palouse study. The basic model includes elevation, slope, aspect, physiographic position, stand level (one- or multistoried), stand density, and presence of volcanic ash. This information could be obtained for all stands on the district from contour maps, resource photography, and soil type maps. Other predictive models also included stand age and/or percentage of host as independent variables. Data on these latter variables were obtained from stand examination records; however, information was not available for all stands.

A predicted probability of defoliation was calculated for each of 496 stands, using the model appropriate to the amount of data available for the particular stand. These values are currently being color coded onto stand boundary maps, using 20 percent probability classes. In addition, a manuscript is being prepared that documents the equipment, data bases, procedures, and manpower required to apply the risk-rating model.

A second step is now in the planning stage. For those stands rated as having a moderately high to high probability of defoliation, a predicted defoliation level will be calculated using the model developed in the Palouse Range study. This is only intended to demonstrate the procedures necessary to apply the risk-rating model. In addition, four stands will be chosen for evaluation of silvicultural treatments aimed at reducing future tussock moth damage. These stands represent the following conditions: (1) stands on high-risk sites containing a large proportion of mature to overmature host trees, (2) multistoried stands on high-risk sites having a mixture of host species and age classes, (3) young stands on high-risk sites with a high proportion of host species but containing sufficient nonhost species to be adequately stocked at harvest age, and (4) young stands on high-risk sites containing only host species.

Two silvicultural prescriptions will be developed for each stand, one recognizing the tussock moth hazard in the stand and the other disregarding this hazard. Using the integrated DFTM model, the consequences of these alternative prescriptions on stand yield, future tussock moth hazard, and economic considerations will be compared. Based on this, we hope to evaluate the usefulness of the risk-rating technology for short- and long-term forest management planning.

IMPLICATIONS OF THE MODELS

The fact that a statistically significant empirical relationship between defoliation and some site or stand characteristic has been found does not necessitate that the characteristics have a controlling influence on tussock moth dynamics. Such a result could occur by chance or reflect some general environmental condition that influenced both the insect and that particular characteristic. On the other hand, the general similarity of results of these two risk-rating studies and further evidence from other studies indicates that some sort of linkage between the condition of the site and stand and the dynamics of the insect does exist.

One possible link is the quality of the foliage consumed by the insect, which is known to affect insect survival and fecundity. Thus, site and stand conditions may influence the tussock moth by determining the physiological status of the host tree and, hence, the biochemical composition of the foliage. When viewed from this angle, the various trends in defoliation can be interpreted in a consistent manner. In general, the risk-rating results imply that outbreaks are associated with conditions where tree competition for moisture and nutrients may be great: upper slopes and ridgetops, low productivity sites, and old, dense stands. These conclusions support the hypothesis by Mattson and Addy (1975) that phytophagous insects act as regulators of forest primary production, their actions varying inversely with the vigor of the forest.

These conclusions have a number of implications for the way in which we manage the forest. On one hand they imply

that many of our past activities have increased the likelihood of serious tussock moth outbreaks. Fire suppression has encouraged the regeneration and development of semitolerant and tolerant host trees on marginal sites for those species (i.e., Douglas-fir on Douglas-fir climax sites and grand fir on grand fir climax sites), leading to the development of dense, low-vigor stands. Recent results indicate that such stands are prime candidates for tussock moth outbreaks (Martin and Williams,[5] Wickman 1978b). Selective logging (high-grading) has had a similar impact, leaving behind poor-quality, low-vigor trees and encouraging regeneration of semitolerant and intolerant host species; serious tussock moth defoliation has occurred in many of these stands.

Direct control of the insect may also fit into this category; while control efforts have been successful in preventing excessive tree mortality, they have also maintained those stand conditions which appear to have encouraged the outbreak to develop in the first place.

On the other hand, the conclusions imply that we have the potential for reducing future tussock moth damage through silvicultural treatment. Practices designed to conserve or enhance soil moisture and nutrients and maintain vigorous tree growth appear to be appropriate. Basically all this means is that we need better management of our forests. Perhaps, from this standpoint, the tussock moth will prove to be a benefit in that we can use the potential of future timber losses to the tussock moth as a justification for more expenditures on silvicultural treatment today.

While no formal validation of either of the riskrating systems described in this paper has been conducted, the agreement between the two studies does lend support to their validity. Similar associations between tussock moth defoliation and site and stand characteristics have also been found in other studies. However, if trends in the past continue to hold true, the ultimate test for validity is just around the corner. In 1982 a 10-year span since initiation of the last outbreak will have elapsed; thus a new outbreak could be expected to develop. As the last outbreak had negligible effect on stand conditions in the Palouse Range, those stands hit in 1973 should again be defoliated, if our reasoning is correct.

[5] Unpublished report by R. E. Martin and J. T. Williams. 1977. A timber type evaluation of historical DFTM outbreak areas in Oregon and Washington. 47 p. Final Rep., USDA DFTM Res. Develop. Prog., Corvallis, Ore.

LITERATURE CITED

Beckwith, R. C. 1978. Biology of the insect: introduction. *In* The Douglas-fir tussock moth: a synthesis. p. 25. M. H. Brookes, R. W. Stark, and R. W. Campbell, eds. U.S. Dep. Agric., Tech. Bull. 1585. Comb. For. Pest Res. Develop. Prog., Corvallis, Ore.

Brown, J. K. 1978. Weight and density of crowns of Rocky Mountain conifers. 56 p. U.S. Dep. Agric. For. Serv., Res. Pap. INT-197. Intermountain For. Range Exp. Stn., Ogden, Utah.

Colbert, J. J., and R. W. Campbell. 1978. The integrated model. *In* The Douglas-fir tussock moth: a synthesis. p. 216-230. M. H. Brookes, R. W. Stark, and R. W. Campbell, eds. U.S. Dep. Agric., Tech. Bull. 1585. Comb. For. Pest Res. Develop. Prog., Corvallis, Ore.

Heller, R. C., and S. A. Sader. 1980. Rating the risk of tussock moth defoliation using aerial photographs. 21 p. U.S. Dep. Agric., Agric. Handb. 569.

Hoerl, A. E., and R. W. Kennard. 1970. Ridge regression: biased estimation for nonorthogonal problems. Technometrics 12:55-67.

Lessard, E. D. 1974. Climatic, host tree, and site factors affecting the population dynamics of the Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough). M.S. thesis, University of Washington, Seattle. 69 p.

Mason, R. R., and R. F. Luck. 1978. Population growth and regulation. *In* The Douglas-fir tussock moth: a synthesis. p. 41-47. M. H. Brookes, R. W. Stark, and R. W. Campbell, eds. U.S. Dep. Agric., Tech. Bull. 1585. Comb. For. Pest Res. Develop. Prog., Corvallis, Ore.

Mattson, W. J., and N. D. Addy. 1975. Phytophagous insects as regulators of forest primary production. Science 190:515-522.

Stage, A. R. 1976. An expression for the effect of aspect, slope, and habitat type on tree growth. For. Sci. 22: 457-460.

Stage, A. R. 1978. Modeling probability of outbreak occurrence and stand involvement. *In* The Douglas-fir tussock moth: a synthesis. p. 59-61. M. H. Brookes, R. W. Stark, and R. W. Campbell, eds. U.S. Dep. Agric., Tech. Bull. 1585. Comb. For. Pest Res. Develop. Prog., Corvallis, Ore.

Stoszek, K. J., P. G. Mika, J. A. Moore, and H. L. Osborne. 1981. Relationships of Douglas-fir tussock moth, *Orgyia pseudotsugata*, defoliation to site and stand characteristics in Idaho. For. Sci. [In press.]

Sudgen, B. A. 1957. A brief history of outbreaks of Douglas-fir tussock moth, *Hemerocampa pseudotsugata* McD., in British Columbia. Entomol. Soc. B. C. Proc. 54:37-39.

Tunnock, S. 1973. The Douglas-fir tussock moth in the northern region--a cartographic history of the outbreaks from 1928-1973. 18 p. U.S. Dep. Agric. For. Serv., Div. State and Priv. For., Rep. 73-27. Missoula, Montana.

Walker, S. H., and D. B. Duncan. 1967. Estimation of the probability of an event as a function of several independent variables. Biometrika 54: 167-179.

Wickman, B. E. 1963. Mortality and growth reduction of white fir following defoliation by the Douglas-fir tussock moth. 15 p. U.S. Dep. Agric. For. Serv., Res. Pap. PSW-7. Pacific Southwest. For. Range Exp. Stn., Berkeley, Calif.

Wickman, B. E. 1978a. Tree injury. *In* The Douglas-fir tussock moth: a synthesis. p. 66-76. M. H. Brookes, R. W. Stark, and R. W. Campbell, eds. U.S. Dep. Agric., Tech. Bull. 1585. Comb. For. Pest Res. Develop. Prog., Corvallis, Ore.

Wickman, B. E. 1978b. A case study of a Douglas-fir tussock moth outbreak and stand conditions 10 years later. 22 p. U.S. Dep. Agric. For. Serv., Res. Pap. PNW-224. Pacific Northwest. For. Range Exp. Stn., Portland, Ore.

Wickman, B. E., and R. C. Beckwith. 1978. Life history and habits. *In* The Douglas-fir tussock moth: a synthesis. p. 30-36. M. H. Brookes, R. W. Stark, R. W. Campbell, eds. U.S. Dep. Agric., Tech. Bull. 1585. Comb. For. Pest Res. Develop. Prog., Corvallis, Ore.

STAND SUSCEPTIBILITY TO GYPSY MOTH DEFOLIATION

Harry T. Valentine and David R. Houston[1]

Abstract.--Susceptible stands of *Quercus* and associated species are defoliated frequently by *Lymantria dispar* (L.) and possibly serve as outbreak foci. These stands, typically on dry upper slopes and ridgetops, sandy plains, and areas of recent disturbance, contain trees that abound with refuges used by endemic populations of *L. dispar* for larval resting, pupation, and oviposition. Resistant stands are infrequently defoliated, primarily by immigrant populations established by wind-dispersed larvae. Because trees in these stands tend to have few refuges, *L. dispar* seek refuge in forest litter, where they often fall prey to animals of the forest floor. We developed discriminant functions that identify stand susceptibility from counts and measurements of refuges on trees of the white oak group and other preferred and nonpreferred food species.

SUSCEPTIBILITY TO DEFOLIATION

The gypsy moth *(Lymantria dispar* [L.]) is an important insect defoliator of oak *(Quercus* spp.) and associated species in northeastern hardwood forests. Bess et al. (1947) classified stands as susceptible or resistant to defoliation by the gypsy moth according to the frequency of defoliation. The susceptibility categories do not consider the effects or consequences of defoliation. Gypsy moth populations frequently reach levels sufficient to cause complete defoliation in susceptible stands. We suspect that many susceptible stands may serve as outbreak foci, i.e., geographic locations where processes permit gypsy moth populations to persist and at times to increase rapidly. Such locations may serve as larval reservoirs from which widespread infestations emanate through the dispersal of first-instar larvae.

Gypsy moth populations normally do not increase to significant levels in resistant stands. However, resistant stands may be defoliated severely when immigrant populations are blown into them. Immigrant populations tend to be reduced quickly in resistant stands, within 2 or 3 years; barring stand disturbance, populations do not increase to significant levels unless more larvae are blown in.

DEFOLIATING POPULATIONS

Gypsy moth larvae hatch from overwintered eggs at the time of budbreak of their host tree species. An infestation is spread mainly through airborne dispersal of early, usually first, instar larvae just after hatch. At hatch, larvae average about 0.2 mg dry weight and are quite buoyant in moving air.

Throughout the larval stadia, a gypsy moth's daily consumption of foliage (dry weight) may exceed its own dry weight. In a recent study (Valentine and Talerico 1980), gypsy moth larvae were found to have an accumulative consumption of 1.1 g of red oak *(Q. rubra)* foliage over a period of 647 Celsius degree days spanning 43 days. During this period their average dry weight increased from 0.2 to 113.1 mg. Mature red oak leaves average 0.5 to 0.7 g, so a gypsy moth larva may consume the equivalent of two mature leaves during its development. However, since early instars consume expanding foliage, actual accumulative consumption of a larva whose final weight is 0.1 g may exceed two leaves. And, since a larva drops some of what it tries to eat, a defoliating population may consist of one insect per three or four oak leaves.

A red oak 38 cm (15 in) in d.b.h. may have in excess of 20 kg of foliage, which would require up to about 18,000 larvae of final dry weight 0.1 g to defoliate it completely. Sixth-instar (the final instar for females) larvae frequently grow to 0.4 g dry weight; so, in actuality, fewer than 18,000 larvae may be adequate to defoliate the tree. On a hectare, there might be 2,000 kg of host foliage in a well-stocked resistant stand, and this would require nearly 200,000 larvae of 0.1 g final weight (with 100 percent survivorship) to cause complete defoliation. Susceptible stands tend to occur on poor sites, or sites subject to frequent disturbance. Foliage biomass may be half that of a well-stocked resistant stand on a good site, and defoliating populations would be proportionately smaller.

A sensitivity analysis of a dynamic model of defoliation, in which the effects of gypsy moth mortality agents were consid-

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ered, suggested that 600,000 to 1,200,000 larvae at hatch would be needed to cause a heavy defoliation of a hectare with 2,000 kg of foliage (Valentine 1979). Assuming 300 eggs per egg mass and no migration, this defoliation would require a population of 2,000 to 4,000 successfully mated females per hectare in the prior year. (Eggs per egg mass may range from 75 to 800, but masses generally tend to be all large or all small in a given area in a given year.) It is interesting to note that in the sensitivity analysis, the parameters that regulated larval consumption rate and growth and foliage growth affected defoliation level much more than did adjustments in larval mortality rates.

Nevertheless, mortality rates have an extremely important effect on final defoliation levels, and we suspect that mortality rates in small populations of larvae may be influenced by larval use of certain structural features of the trees (Bess et al. 1977, Houston and Valentine 1977, Valentine and Houston 1979, Houston 1979, Campbell and Sloan 1977, Campbell et al. 1977).

BEHAVIOR-RELATED MORTALITY

Innumerable studies have shown that fourth-, fifth-, and sixth-instar larvae ascend their hosts in the evening and feed during the night. In the morning, they descend and seek shelter. An exception is when host foliage is in short supply; then larvae may search for and consume foliage around the clock.

Bess et al. (1947) observed that in resistant stands, where larval populations were too low to cause significant defoliation, late-instar larvae could often be found during the day in loose ground litter. In contrast, few late-instar larvae were found in the litter during the day in susceptible stands with high larval populations. And further, survival of larvae was much enhanced when they molted and rested above the forest floor rather than in litter on the ground.

More recently, Campbell et al. (1975a) studied an area of northeastern Connecticut that had supported only sparse, stable populations for many years. In corroboration of Forbush and Fernald (1896), the Campbell team observed that instars 1 through 3 tended to stay in the foliage. Before molting to instar 4, however, larvae began seeking daytime resting or hiding locations. In those resistant Connecticut stands, these locations were usually in the litter at the base of the tree host, which corroborated the observations of Bess et al. (1947).

Bess et al. (1947) conjectured that poor survival of late-instar litter-resting larvae could be attributed to predation by litter-foraging small mammals and arthropods. Campbell et al. (1977) also attributed most larval mortality in the litter to density-dependent predators. Campbell and Sloan (1976) further indicated that the white-footed mouse, *Peromyscus leucopus* Raf., killed about 70 percent of the pupae in the resistant stands studied. (Pupation and larval resiting locations are often the same.) Mortality rates were higher in the litter than in other locations, and disproportionately more female pupae than males were killed by vertebrate predators. Campbell et al. (1975b) said that tree bark flaps provided virtually the only pupation locations in the resistant stands they studied where female pupae had a "reasonable" probability of survival.

An extensive list of gypsy moth predators is given by Smith and Lautenschlager (1978). Although the effectiveness of predators, including mammals, generally remains unknown, an effective control potential in resistant stands is recognized. As noted above, if larvae are unable to find adequate shelter on trees, they often seek it in the litter, where predators forage. Mammals, being warm blooded with high metabolic rates, require large amounts of food to maintain their body temperatures. Moreover, they have highly developed learning abilities. Smith and Lautenschlager (1978) pointed out that mammals learn where larvae congregate, concentrate their prey searches in these areas, and often learn to avoid insect defense mechanisms. While certain predators may kill significant numbers of larvae or pupae in small populations of gypsy moths, the gypsy moth, not being exclusive prey, may have little influence on the numerical changes in predator populations.

THE STRUCTURAL FEATURE HYPOTHESIS

Bess et al. (1947) noted that more gypsy moth larvae survived when they stayed on the trees than when they hid in the litter. Susceptible stands, where this was typically observed, were dry open woodlands containing scant ground litter and composed mostly of preferred hosts. These stands occurred mainly on well-drained sandy soils or on high rocky ridges. Other susceptible stands had histories of disturbance. Resistant stands were well stocked with vigorous trees, deep litter, and, on loamy soils, with mesic moisture conditions. Bess et al. (1947) went on to list plant indicators whose presence and abundance should be used in conjunction with an examination of stand stocking, tree vigor, site moisture conditions, physiography, and dis-

turbance to identify stand susceptibility to gypsy moth defoliation.

Our own efforts to develop a discriminant function for identifying stands susceptible to gypsy moth defoliation (Valentine and Houston 1979) were based largely on the keen observations of Bess et al. (1947), and the following hypothesis: gypsy moth larval survival is higher in susceptible stands because of an abundance of suitable resting or hiding locations on the host trees themselves. We assume that larvae use these locations on the trees instead of the litter, where survival is low. What we term structural features include bark flaps, holes and wounds, deep bark fissures, large dead branches in lower tree crowns, and crooked or sweeping tree boles.

Use of the structural features by larvae during the day keeps them out of reach of litter-foraging predators, and out of sight of avian predators. Although such predation in conjunction with other control agents may keep larval populations from reaching defoliating levels in resistant stands, use of the structural features may augment larval and pupal survival in susceptible stands and yield large egg populations for the next year. Once populations have exceeded a certain threshold, predators may become inconsequential as control agents, because few predator populations respond numerically to changes in gypsy moth density. A similar scenario has been advanced by Campbell and Sloan (1977).

Structural features abound in susceptible stands but are relatively scarce in resistant stands. While we did not test the survival hypothesis per se, we were successful in discriminating between historically resistant and susceptible mixed oak stands with counts and measurements of structural feature variables (Houston and Valentine 1977, Valentine and Houston 1979). The discriminant function does not rely on species and species associations, or site conditions found in New England, or on the perspicacity of individuals as does the subjective identification procedure of Bess et al. (1947). Rather, our system is based on measurable elements of habitat that may directly limit gypsy moth success in resistant stands and prevent control agents from keeping gypsy moth populations at innocuous levels in susceptible stands.

DISCRIMINANT FUNCTION DEVELOPMENT

The discriminant function that identifies mixed-oak stand susceptibility to gypsy moth defoliation and descriptions of the data used to develop the discriminant function are given elsewhere (Houston and Valentine 1977, Valentine and Houston 1979). Here we will give further details about our statistical analysis and our intermediate results, details which were not reported before.

Data were used from 121 stands, 77 of which were either historically susceptible or had encountered gypsy moths recently and were judged by us to be susceptible to gypsy moth defoliation. In all cases, the positions of the suspect stands in three different principal component ordinations (Houston and Valentine 1977) were close to those of historically susceptible stands, and met the criteria of Bess et al. (1947). The remaining 44 stands were either historically resistant to gypsy moth defoliation or were recently infested stands suspected of being resistant. These suspect stands met the criteria of Bess et al. (1947) for resistant stands and passed our ordination test.

The stands were located in New England, New Jersey, and parts of Pennsylvania and New York. The physiography of the sites ranged from dry ridges to slopes to mesic slopes and bottomlands. Dry Atlantic Coastal Plain sites were also sampled. All 121 stands were predominantly oak, and all had at least one species of the red oak group and the white oak group.

The variables used in the discriminant analysis were the following, measured on a 0.25-acre basis[2]:

x_1 = natural logarithm of the quantity 1 plus the number of discrete structural features (defined below) on trees of the white oak group (white oaks have been considered preferred hosts). (The discrete structural features consisted of bark flaps, holes, and wounds on boles of live trees [d.b.h. > 2.5 inches or 6.35 cm] from the ground to 6 ft [1.8 m] and large-diameter [> 1.0 inch or 2.54 cm] dead branches beneath the live crown.)

x_2 = natural logarithm of the quantity 1 plus the number of discrete structural features on other species considered preferred hosts. (See table 1 for preferred and nonpreferred host tree species.)

x_3 = natural logarithm of the quantity 1 plus the number of discrete structural features on species considered nonpreferred hosts.

x_4 = sum of diameters of trees with bark fissures ≧ 0.5 inch (1.27 cm) plus ¼ of the sum of diameters of trees with crook or sweep in the white oak group.

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[2] The list of variables and table 1 are reprinted with the permission of the editors of "Forest Science."

x_5 = sum of diameters of trees with deep bark fissures plus ¼ of the sum of diameters of trees with crook or sweep in the other preferred class.

x_6 = sum of diameters of trees with deep bark fissures plus ¼ of the sum of diameters of trees with crook or sweep in the nonpreferred class.

x_7 = sum of diameters of white oak group with neither deep bark fissures nor crook or sweep.

x_8 = sum of diameters of other preferred host trees with neither deep bark fissures nor crook or sweep.

x_9 = sum of diameters of nonpreferred host trees with neither deep bark fissures nor crook or sweep.

Summary statistics for the nine variables are given in table 2.

We determined the best subset of the nine discriminatory variables to include in a discriminant function with the Furnival and Wilson (1974) "leaps and bounds" regression program. This program selects the best (i.e., maximum R^2) variable to use in a one-variable regression, the best two variables to use in a two-variable regression, and so forth. It also selects

Table 1.--Food preference classes of the host tree species defined for the discriminant analysis

White oak	Other preferred	Nonpreferred	
Quercus alba	*Alnus* spp.	*Acer rubrum*	*Magnolia acuminata*
Q. prinus	*Betula papyrifera*	*A. saccharum*	*Nyssa sylvatica*
	B. populifolia	*Aesculus glabra*	*Ostrya virginiana*
	Malus spp.	*Amelanchier canadensis*	*Picea rubens*
	Populus grandidentata	*Carpinus caroliniana*	*Pinus pungens*
	P. tremuloides	*Carya cordiformis*	*P. resinosa*
	Q. coccinea	*C. glabra*	*P. rigida*
	Q. ilicifolia	*C. ovata*	*P. strobus*
	Q. marilandica	*C. tomentosa*	*P. sylvestris*
	Q. rubra	*Castanea dentata*	*P. virginiana*
	Q. stellata	*Celtis occidentalis*	*Prunus serotina*
	Q. velutina	*Cornus florida*	*Robinia pseudoacacia*
	Tilia americana	*Diospyros virginiana*	*Rhus* spp.
		Fagus grandifolia	*Sassafras albidum*
		Fraxinus americana	*Tsuga canadensis*
		Hamamelis virginiana	*Ulmus americana*
		Juglans cinerea	*U. rubra*
		J. nigra	
		Juniperus virginiana	
		Liriodendron tulipifera	

Table 2.--Stand means and standard deviations of the discriminant function variables according to susceptibility group, and the Mahalanobis distance between the group means - the squared difference between the group means divided by the pooled within-group variance.

Variable	Mean		Standard deviation		Mahalanobis distance
	Resistant	Susceptible	Resistant	Susceptible	
x_1	3.31	4.95	1.00	0.65	4.27[a]
x_2	3.62	4.38	1.28	1.09	0.43
x_3	4.34	4.82	0.94	1.19	0.19
x_4	57.35	172.53	80.22	154.43	0.76
x_5	50.82	50.87	49.00	52.36	0.00
x_6	38.04	51.29	36.48	59.30	0.06
x_7	121.75	113.84	98.44	88.41	0.00
x_8	174.32	158.13	111.17	103.92	0.02
x_9	180.35	118.08	97.07	77.36	0.54

[a] F to test no difference between group means transformed with a single variable discriminant function equals 28 · Mahalanobis distance with 1 and 119 df.

the second best, third best, and up to tenth best subset of variables for each size regression.

A discriminant function can be calculated by regressing a dummy "dependent" variate indicating the sampled individuals' group memberships on the discriminatory variables. The value of the dummy variate (y) is

$$y_i = \frac{n_r}{n_s + n_r}$$

if the *i*th individual belongs to group s, or

$$Y_i = - \frac{n_s}{n_s + n_r}$$

if the *i*th individual belongs to group r. For our purposes, the "individuals" were stands, n_s was the number of susceptible stands, and n_r was the number of resistant stands. The coefficients resulting from the regression of y on the discriminatory variables will be proportional to the coefficients obtained using the normal likelihood approach to discriminant analysis:

$$\Sigma^{-1} (x_r - x_s)$$

where Σ^{-1} is the inverse of the pooled-sample within-group covariance matrix, and x_r and x_s are the mean vectors of discriminatory variables for group r and s, respectively.

The Mahalanobis distance (D^2) is the difference between the discriminant scores of the two group means

$$D^2 = (x_r - x_s)' \Sigma^{-1} (x_r - x_s).$$

D^2 increases monotonically with R^2, i.e.,

$$D^2 = R^2/(1-R^2) \cdot (n_r+n_s)(n_r+n_s-2)/n_r n_s,$$

provided the regression variate is dichotomous (Lachenbruch 1975). Thus, the leaps and bounds regression selects the subset of discriminatory variables that maximizes the separation of group means for each size subset. A stepwise procedure does not necessarily do this. If the discriminatory variables are normally distributed and the group covariance matrices are equal, then the true linear discriminant function will be optimal. That is, it will have the lowest possible total probability of misidentification (*see*, e.g., Lachenbruch 1975). In our case, neither the normality nor covariance criteria were met. Nevertheless, the linear discriminant function provided a reasonable separation of the two groups of stands.

Below are the discriminant functions obtained using leaps and bounds regression. Here the subscripts of x refer to the discriminatory variables defined above, and the subscripts of Y denote the discriminant function. With any of these functions a stand should be identified as susceptible if $Y_i<0$ and resistant if $Y_i \geq 0$.

(1) $Y_1 = 10.76 - 2.60\, x_1$

(2) $Y_2 = 14.02 - 2.71\, x_1 - 0.62\, x_3$

(3) $Y_3 = 11.89 - 2.75\, x_1 - 0.012\, x_6$

(4) $Y_4 = 12.82 - 2.59\, x_1 - 0.53\, x_2$

(5) $Y_5 = 13.66 - 2.58\, x_1 - 1.02\, x_3 + 0.011\, x_9$

(6) $Y_6 = 15.43 - 2.48\, x_1 - 0.97\, x_3 - 0.0079\, x_4$

(7) $Y_7 = 13.89 - 2.28\, x_1 - 0.92\, x_2 - 0.0070\, x_5$

(8) $Y_8 = 15.45 - 2.24\, x_1 - 1.60\, x_3 - 0.0087\, x_4 + 0.014\, x_9$

(9) $Y_9 = 17.84 - 2.68\, x_1 - 1.05\, x_3 - 0.0091\, x_4 - 0.017\, x_5$

(10) $Y_{10} = 18.61 - 2.64\, x_1 - 1.09\, x_3 - 0.011\, x_4 - 0.0090\, x_8$

(11) $Y_{11} = 17.56 - 2.44\, x_1 - 1.62\, x_3 - 0.0011\, x_4 - 0.016\, x_5 + 0.013\, x_9$

(12) $Y_{12} = 17.98 - 2.39\, x_1 - 1.63\, x_3 - 0.012\, x_4 - 0.0072\, x_8 + 0.013\, x_9$

(13) $Y_{13} = 17.72 - 2.14\, x_1 - 0.65\, x_3 - 0.011\, x_4 + 0.011\, x_9$

The "best" discriminant functions with 1, 2, 3, 4, and 5 variables are (1), (2), (5), (8), and (11), respectively. The Mahalanobis distances and the error rates, calculated by the leaving-one-out method (Lachenbruch 1967), are given in table 3 for all 13 functions.

In selecting which discriminant function to use, we use statistics and other considerations. In most cases one would use the best function whose variables all contribute significantly to the Mahalanobis distance.

In the leaps and bounds procedure, an α level of .01 or .005 might be used to indicate significance since so many regressions are tested. However, practical considerations entered our deliberation, and we chose function (8) (Valentine and Houston 1979). Function (8) does not require any measurements or counts for

trees in the preference class "other preferred." Accordingly, data acquisition is much easier. All the variables are significant ($P < .005$) and the error rates are reasonable (table 3). The same could be said for function (5), which requires no measurements of sums of diameters of crooked or sweeping trees, or trees with deep bark fissures.

However, we felt that (8), in which the influence of crook, sweep, and deep bark fissures of white oak group species is included, would be more robust in the long run, especially if the discriminant function is applied in areas where the gypsy moth is extending its range. The two species of the white oak group encountered in our sample, *Q. prinus* and *Q. alba*, are both preferred hosts, and both have an abundance of structural features, particularly when growing on poor sites. Whereas *Q. alba* has a tendency to produce bark flaps, which contribute to x_1, *Q. prinus* has a tendency to produce deep bark fissures, crook, and sweep, which contribute to x_4. Many of the drier ridges in the southwestern part of our sample region, and ridges south and west of this region, are dominated by *Q. prinus*. Accordingly, (8), the best four-variable function that contains both x_1 and x_4, seems best on ecological, as well as practical and statistical grounds.

DISCUSSION

The problem of selecting variables for inclusion in a discriminant function is discussed by Lachenbruch (1975). He indicated that performing tests on the Mahalanobis distance to find the best of all possible subsets of k variables would require 2^k-1 tests, which is not feasible computationally. However, the very efficient leaps and bounds regression algorithm (Furnival and Wilson 1974) will find the best subsets of size p, $p = 1, 2, \ldots, k-1$, without examining all possible subsets. Since a two-group discriminant function is easily set up as a regression model, the leaps and bounds algorithm is an extremely powerful tool, if one chooses to use the subset of discriminatory variables of size $p < k$ that maximizes the Mahalanobis distance.

Of course, how good a best subset is depends on the adequacy of the discriminatory variables. We developed our original set of nine discriminatory variables based on our understanding about how tree structural features influence gypsy moth larval and pupal survival. The discriminatory variables x_1 through x_3 were developed to partially account for the number of larval resting, pupation, and oviposition sites per acre on trees in each of the three food preference classes. These sites may enhance gypsy moth survival by affording protection from litter-foraging control agents.

Variable x_1, the log count of discrete structural features on trees of the white oak group, was found to have excellent discriminatory power. It is included in all 13 leaps and bounds discriminant functions, and the estimated error rate of function (1), the discriminant function based on x_1 alone, is lower for susceptible stands than the error rate of function (8), the best four-variable function.

Variables x_4 through x_6 are supposed to index the amount of bole surface area having deep bark fissures and amount of area used by gypsy moths on boles with crook and sweep in each of the three food preference classes. When used, these features keep gypsy moths away from litter-foraging predators, but they offer little protection from avian predators.

Variables X_7 through x_9 were developed to index the area of bole surface where larvae and pupae would be most vulnerable to parasites and certain predators, especially birds. In the discriminant functions in which x_9 is included, its sign is opposite that of variables x_1 through x_6, implying that increases in straight-boled, shallow-fissured hosts are associated with increases in the probability of stand resistance.

The discriminatory variables also reflect tree responses to disturbance and site quality. Although susceptible stands tend to occur on poor sites, and resistant ones on better sites, we did not utilize site index nor other standard inventory variables in our discriminant functions. Any conceived increase in the probability of stand susceptibility due to increases or decreases in such inventory variables would require additional justification, and would result, we suspect, in broad statements of association between inventory variables and factors limiting gypsy moth population increases. However, we contend that by measuring structural features, we directly measured some of the limiting factors.

A discriminant function based on inventory variables would perhaps be useful in estimating the amount of susceptible forest in an area from existing inventory data. However, we see the critical question being addressed by the prognosticating silviculturist in the development of a stand or work unit management plan: Is a given stand susceptible to gypsy moth defoliation, or not? The discriminant function (8) and some others will make that identification correctly more than 85 percent of the time. We suspect that

Table 3.--Mahalanobis distance and error rates of discriminant functions that identify mixed oak stand susceptibility to gypsy moth defoliation

Discriminant function	Variables	Mahalanobis distance	F[a]	Error rates[b]	
				Resistant	Susceptible
1	x_1	4.27	119.5(1,119)	.273	.091
2	x_1, x_3	4.74	65.8(2,118)	.250	.091
3	x_1, x_6	4.68	65.0(2,118)	.182	.104
4	x_1, x_2	4.65	64.6(2,118)	.205	.091
5	x_1, x_3, x_9	5.40	49.5(3,117)	.136	.104
6	x_1, x_3, x_4	5.28	48.6(3,117)	.182	.104
7	x_1, x_2, x_3	5.23	48.0(3,117)	.227	.091
8	x_1, x_3, x_4, x_9	6.32	43.1(4,116)	.136	.104
9	x_1, x_3, x_4, x_5	5.95	40.6(4,116)	.182	.065
10	x_1, x_3, x_4, x_8	5.92	40.4(4,116)	.205	.104
11	x_1, x_3, x_4, x_5, x_9	6.84	37.0(5,115)	.159	.052
12	x_1, x_3, x_4, x_8, x_9	6.71	36.3(5,115)	.136	.117
13	x_1, x_2, x_3, x_4, x_9	6.71	36.3(5,115)	.136	.091

[a] F to test Mahalanobis distance equal to zero; degrees of freedom in parentheses.

[b] Error rates calculated by the leaving-one-out method.

with repeated use, one should develop the ability to make a subjective judgment of stand susceptibility with equal accuracy.

Ascertaining the susceptibility of stands to gypsy moth defoliation should be an important part of a regional gypsy moth management system. If susceptible stands serve as foci for widespread infestation, or if processes that lead to defoliating populations in susceptible stands presage similar processes in larger areas, then susceptible stands should be identified and gypsy moth populations monitored yearly. Whether actions taken to quell defoliating populations in susceptible stands would prevent widespread infestations is a subject for further research. However, until such information becomes available, it would seem reasonable to compute expected discounted marginal benefits of control operations using subjective probabilities of the spread of infestations, with the assumption that control operations in susceptible stands would prevent widespread infestations.

LITERATURE CITED

Bess, H. A., S. H. Spurr, and E. W. Littlefield. 1947. Forest site conditions and the gypsy moth. 56 p. Harvard For. Bull. No. 22.

Campbell, R. W., D. L. Hubbard, and R. J. Sloan. 1975a. Patterns of gypsy moth occurrence within a sparse and numerically stable population. Environ. Entomol. 4:535-542.

Campbell, R. W., D. L. Hubbard, and R. J. Sloan. 1975b. Location of gypsy moth pupae and subsequent pupal survival in sparse, stable populations. Environ. Entomol. 4:597-600.

Campbell, R. W., and R. J. Sloan. 1976. Behavioral evolution and gypsy moth pupal survival. Environ. Entomol. 5: 1211-1217.

Campbell, R. W., and R. J. Sloan. 1977. Natural regulation of innocuous gypsy moth populations. Environ. Entomol. 6:315-322.

Campbell, R. W., R. J. Sloan, and C. E. Biazak. 1977. Sources of mortality among late instar gypsy moth larvae in sparse populations. Environ. Entomol. 6:865-871.

Forbush, E. H., and C. H. Fernald. 1896. The gypsy moth. 495 p. State Board of Agriculture, Boston, Mass.

Furnival, G. M., and R. W. Wilson, Jr. 1974. Regressions by leaps and bounds. Technometrics 16:499-511.

Houston, D. R. 1979. Classifying forest susceptibility to gypsy moth defoliation. 24 p. U.S. Dep. Agric., Agric. Handb. 542.

Houston, D. R., and H. T. Valentine. 1977. Comparing and predicting forest stand susceptibility to gypsy moth. Can. J. For. Res. 7:447-461.

Lachenbruch, P. A. 1967. An almost unbiased method of obtaining confidence intervals for the probability of misclassification in discriminant analysis. Biometrics 23:639-645.

Lachenbruch, P. A. 1975. Discriminant analysis. 128 p. Hafner Press, New York.

Smith, H. R., and R. A. Lautenschlager. 1978. Predators of the gypsy moth. 72 p. U.S. Dep. Agric., Agric. Handb. 534.

Valentine, H. T. 1979. A model of oak forest growth under gypsy moth influence. *In* The gypsy moth: research toward integrated control. U.S. Dep. Agric., Tech. Bull. 1584. [In press.]

Valentine, H. T., and D. R. Houston. 1979. A discriminant function for identifying mixed-oak stand susceptibility to gypsy moth defoliation. For. Sci. 25: 468-474.

Valentine, H. T., and R. L. Talerico. 1980. Gypsy moth consumption and growth on red oak. For. Sci. 26:599-605.

HAZARD RATING OF STANDS FOR SOUTHERN PINE BEETLE ATTACK IN ARKANSAS

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INTRODUCTION

Before 1969, the occurrence of the southern pine beetle (SPB), *Dendroctonus frontalis* Zimm., in Arkansas was only sporadic. Beginning in that year, however, the insect apparently entered the State in the southeast corner and began a slow but steady spread north and west through the State's productive pine lands. This progress culminated in an epidemic in 1975 through 1977; at its peak 24 counties reported outbreaks.

In an effort to typify those sites and stands that were most susceptible to attack, the Department of Forestry at the University of Arkansas at Monticello and the Arkansas Forestry Commission began a cooperative research project in 1975. The USDA Expanded Southern Pine Beetle Research and Applications Program provided funding under a Southwide site and stand project with the following objectives: (1) to relate frequency and intensity of SPB infestations to site and stand characteristics, (2) to develop descriptive and predictive models that rank forest stands as to SPB susceptibility, and (3) to recommend silvicultural practices and other treatments that reduce SPB infestations.

Two major factors made the Arkansas study unique. Since Arkansas had no recent history of beetle attack, stands were being exposed to the pest for the first time as the epidemic spread. The investigators felt that by definition the attacked stands exhibited the site and stand conditions that predispose stands to attack. The second unique factor was the outstanding cooperative effort of the Arkansas Forestry Commission in providing field personnel to collect the data. The commission made the data collection a part of its routine aerial survey and ground check of beetle activity. The principal investigators held training sessions for field crews. Professional foresters and trained technicians recorded all plot data.

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The total efforts of all field crews created the largest data base of any project in the Southwide program. Furthermore, the distribution of personnel around the State allowed the collection of data in the areas of the earliest and heaviest infestation, even as the front of the epidemic expanded.

PROCEDURES

Between April 1975 and March 1977, over 5,000 SPB spots were detected from the air and ground-checked. Field crews collected data on 41 site and stand variables at 984 randomly selected beetle-infested spots. No plot was taken within 20 chains of another, and most plots were established in the Coastal Plain area.

During this data collection period, we established for purposes of comparison 509 additional uninfested plots in the area of infestation. The first 282 of these plots were taken at a random azimuth and distance between 5 and 10 chains from an infested plot. The final 227 were taken from pine stands located systematically throughout southern Arkansas. As there was no significant difference between the two groups, they were pooled to provide a larger data base for uninfested stands.

RESULTS

Preliminary analysis of the initial 743 infested plots against all uninfested plots (Ku et al. 1976) confirmed reports in earlier studies that site disturbance induces beetle attack (Hodges and Pickard 1971, Lorio and Bennett 1974). Lightning strike and logging activity were the most detrimental types of disturbance (table 1).

Further analysis revealed, however, that despite the effect of disturbance in inducing attack, undisturbed infested stands were larger, had more trees killed, and had a higher average basal area than disturbed infested stands. One possible explanation is that while disturbance may induce attack on a few weakened trees, the attack generally doesn't spread unless the site and/or stand has inherent characteristics predisposing it to SPB attack. We decided to analyze undisturbed plots

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Table 1.--Occurrence of disturbance in infested and uninfested plots[1]

Disturbance	Initial SPB plots (743)		Uninfested plots (509)	
	Occurrence	Percent	Occurrence	Percent
No known disturbance	135	18	247	49
Lightning strike	278	37	3	1
Logging activity within past year	139	19	48	9
Logging activity 1-5 years ago	176	24	101	20
Ice damage	172	23	98	19
Fire within 5 years	17	2	18	4
Herbicide brush control within 5 years	44	6	16	3
Other disturbances	24	3	23	5

[1] A plot may have more than one disturbance.

also since they revealed more about inherent site and stand conditions that predispose attack.

Both loblolly (*Pinus taeda* L.) and shortleaf (*P. echinata* Mill.) were present in the plots. A χ^2 test of SPB-attacked trees *v.* unattacked trees by loblolly *v.* shortleaf within all infested plots indicated that shortleaf was more susceptible to SPB attack ($P < 0.01$). Undisturbed stands yielded the same results.

Using Student's *t* test, we found that attacked trees within all infested plots were significantly younger and shorter and had slower growth rates, lower live crown ratio, and thinner bark than unattacked trees (table 2).

Higher basal area, greater pine/hardwood ratio, thinner bark, and slower growth typified the average infested stand, compared to the uninfested average (table 3). These differences were even more pronounced when only undisturbed plots were analyzed. Besides significantly higher basal area, undisturbed infested stands also exhibited lower live crown ratio, less understory, shorter height, and younger age.

HAZARD RATING DEVELOPMENT

With the results of the above analyses as a basis, we used discriminant analysis to develop the hazard rating (Ku et al. 1980). Originally all 1,493 plots and all continuous variables were subjected to the analysis. Because of the large groups and resulting variability, early trials gave prediction levels of 65 percent. To remove some of the complex variability, we used only undisturbed plots and only strongly discriminating variables for succeeding analyses. We also trued interaction variables such as stress index (basal area/site index) and climax index (number of hardwoods/number of pines). However, as analysis continued, simple variables such as basal area, bark thickness, growth rate, and number of hardwoods present in the plot proved more useful.

Table 2.--Means of attacked and unattacked trees within SPB-infested pine plots in southern Arkansas

Variable	All SPB plots (984)		Undisturbed SPB plots (282)	
	Attacked	Unattacked	Attacked	Unattacked
Age (years)	34 ± 17	36 ± 17[1]	33 ± 17	32 ± 17
D.b.h. (inches)	9.7 ± 4.1	11.0 ± 4.9[1]	9.6 ± 4.0	10.8 ± 4.9[1]
Height (feet)	58.3 ± 18	60.2 ± 28[1]	58 ± 18	58 ± 18
Live crown ratio (%)	38.2 ± 12	42 ± 12[1]	37 ± 12	41 ± 12[1]
Bark ridge (inches)	.71 ± .22	.74 ± .31[2]	.74 ± .23	.74 ± .26
Bark fissure (inches)	.30 ± .10	.32 ± .12[1]	.30 ± .10	.31 ± .12
Bark average (inches)	.51 ± .14	.53 ± .20[1]	.52 ± .15	.53 ± .17
Radial growth (5 yr, cm)	1.75 ± .70	1.89 ± .79[1]	1.71 ± .69	1.79 ± .82
Radial growth (10 yr, cm)	3.66 ± 1.44	3.90 ± 1.59[1]	3.60 ± 1.46	3.80 ± 1.69

[1] $p < .01$

[2] $p < .05$

Table 3.--Mean stand conditions for SPB-infested and uninfested plots in southern Arkansas

Variable	All plots		Undisturbed plots	
	Infested plots (984)	Uninfested plots (509)	Infested plots (282)	Uninfested plots (247)
Average age (yr)	36 ± 16	35 ± 16	32 ± 16	35 ± 16[2]
Average d.b.h., pine only (in)	11.3 ± 3.7	11.6 ± 4.0	10.4 ± 3.3	11.9 ± 4.0[1]
Average height of pine (ft)	61 ± 17	61 ± 17	59 ± 16	62 ± 17[2]
Average live crown ratio (%)	42 ± 9	43 ± 10	39 ± 9	43 ± 10[1]
Average bark thickness (in)	.51 ± .14	.54 ± .12[1]	.51 ± .14	.55 ± .13[1]
5-yr radial growth (cm)	1.84 ± .62	2.02 ± .72[1]	1.75 ± .63	2.00 ± .70[1]
10-yr radial growth (cm)	3.83 ± 1.30	4.16 ± 1.49[1]	3.70 ± 1.35	4.21 ± 1.45[1]
		Basal area (ft^2/acre)		
Total	104 ± 49	98 ± 40[1]	131 ± 44	103 ± 41[1]
Loblolly	71 ± 54	62 ± 44[1]	85 ± 60	66 ± 47[1]
Shortleaf	17 ± 32	11 ± 26[1]	25 ± 42	11 ± 26[1]
Hardwood	17 ± 21	25 ± 27[1]	21 ± 24	26 ± 27[1]
Stand understory (%)	42 ± 29	43 ± 28	33 ± 31	43 ± 30[1]

[1] $p < .01$

[2] $p < .05$

When we used only undisturbed plots in the analysis, the prediction score was about 72 percent, depending on the variables. The groups were further stratified by using only disturbed natural plots on upland flats (the most common landform in south Arkansas). As a result some of the variability was removed and the prediction score rose above 75 percent. The final stratification was done by choosing plots of undisturbed natural stands located on upland flats and having more than 10 infested trees. Previous analyses had shown that plots which represented stands with more infested trees also had the higher basal area--the major inducing factor to SPB attack. This final set of discriminant equations correctly classified plots 80 percent of the time.

The two classification equations thus derived contained so many variables that there would be little practical value for use as a field hazard-rating system. Instead, we removed all impractical, difficult-to-measure variables and reran the analysis using only the following variables: basal area, stand age, radial growth in 10 years, and hardwood basal area. The prediction fell to 75 percent; therefore, these easily measured variables were able to discriminate all but 5 percent of the plots from the previous analysis.

At this point there were 161 uninfested plots and 107 infested plots in the analysis. Ten percent of these plots were randomly selected and removed from the pool (11 infested, 17 uninfested). We ran discriminant analysis on the remaining 240 plots, resulting in a prediction of nearly 75 percent. This was done to determine whether the equations built from the remaining pool could accurately predict the status of those plots that had been left out of this analysis. As expected, 75 percent of the removed plots were correctly classified.

The final equation for field use was built using all 268 plots. The scaled unstandardized discriminant equation thus derived is as follows:

$$Y = -1.50\ TBA + .93\ HBA + 3.3\ SA + 64.3\ RG$$

where: TBA = total basal area (ft^2/acre)
HBA = hardwood basal area (ft^2/acre)
SA = stand age (years)
RG = radial growth in 10 years (nearest one-tenth inch)

All of these variables are fairly easy to measure in the field and as such this equation represents a hazard rating for stands. Stands can be classified as to high, medium, or low susceptibility to SPB attack depending upon the value obtained when the measurements of a particular stand are substituted into the equation. A score above 100 indicates low susceptibility; between 1 and 100 indicates medium susceptibility; less than 1 indicates high susceptibility. These limits (1 and 100) represent the centroids for the two groups of plots (infested and uninfested).

This equation is best applied to un-

disturbed natural stands on upland flats. Its predictive power is greatest on these stands since they made up the data base for the analysis. The equation's ability to predict susceptibility on other landforms, in plantations, or sites with disturbance is unknown; but it may still provide a good indication.

IMPLEMENTATION

Since the development of the hazard rating, we have placed emphasis on relaying the information to landowners with high-hazard stands. In late 1979 a pamphlet entitled "Preventing Damage from the Southern Pine Beetle Through Better Forest Management" was published as a cooperative effort between the Arkansas Forestry Commission, State and Private Forestry, and the Forestry Department of the University of Arkansas at Monticello. The pamphlet not only presents the hazard rating but also makes silvicultural recommendations.

A workshop was held in April 1980 to acquaint Arkansas Forestry Commission personnel with the hazard-rating system since they provide a great deal of forest management assistance to small private landowners. This workshop emphasized not only accurate measurement of stand variables that are a part of the risk rating, but also the necessity of making the landowner aware that pockets of high stand density are potential sites for SPB attack.

A Statewide workshop for the users' group has also been planned for September through the Cooperative Extension Service. The workshop will be conducted by the University of Arkansas at Monticello, the Arkansas Forestry Commission, and State and Private Forestry personnel. The workshop will be designed to help the private landowners implement this hazard-rating system.

The combined message of the hazard rating and goood management advice will hopefully promote the tending of well-managed, vigorous stands. These practices, in turn, may prevent future epidemics and minimize any SPB losses that do occur.

LITERATURE CITED

Hodges, J. D., and L. S. Pickard. 1971. Lightning in the ecology of the southern pine beetle, *Dendroctonus frontalis* Zimm. (Coleoptera:Scolytidae). Can. Entomol. 103:44-51.

Ku, T. T., J. M. Sweeney, and V. B. Shelburne. 1976. Preliminary evaluation of site and stand characteristics associated with southern pine beetle infestations in Arkansas. Ark. Farm Res. 25(5):2.

Ku, T. T., J. M. Sweeney, and V. B. Shelburne. 1980. Site and stand conditions associated with southern pine beetle outbreaks in Arkansas--a hazard rating system. South. J. Appl. For. 4(2):103-106.

Lorio, P. L., Jr., and W. H. Bennett. 1974. Recurring southern pine beetle infestations near Oakdale, Louisiana. U.S. Dep. Agric. For. Serv., Res. Pap. SO-95. South. For. Exp. Stn., New Orleans, La.

USE OF PHYSIOLOGICAL MATURITY TO IDENTIFY HAZARD OF LODGEPOLE PINE STANDS FROM MOUNTAIN PINE BEETLE

D. M. Shrimpton and A. J. Thomson[1]

Abstract.--From research in our laboratory and a historical review of lodgepole pine (*Pinus contorta* Dougl.) stands sustaining mountain pine beetle (*Dendroctonus ponderosae* Hopk.) outbreaks throughout British Columbia, we proposed that to minimize losses from mountain pine beetle, stands should be managed for wood production and therefore harvested no later than the point when they reach physiological maturity. To test this proposal, we obtained growth data from a grove of lodgepole pine near which mountain pine beetle had been active from 1972 through 1979. Twelve dominant and codominant lodgepole pine were cut from the grove. Results of our examination show that the trees were near physiological maturity; therefore, this aspect of our hazard-rating system was confirmed.

INTRODUCTION

A hazard-rating system for mountain pine beetle (MPB) was developed in our laboratory (Safranyik et al. 1975). This system was communicated to those foresters in British Columbia responsible for setting cutting schedules and establishing forest management plans. A series of workshops and personal visits at various locations throughout British Columbia and several publications established lines of communication.

The hazard-rating system recognizes that beetle and trees have different limiting factors. Hazard from the beetles can exist only where climate is favorable for beetle development. Hazard of the trees has two aspects. The first is the definition of a point in the development of a stand when trees, if killed by the beetles, are large enough to sustain the insect population--20 cm (8 in) average stand diameter. In this paper we consider that when stands exceed this 20-cm average diameter, they are prone to beetle damage. The second aspect is the definition of a time period when trees can be readily killed by the beetles; it is this aspect that we term stand hazard. Because resistance to beetle attack and incremental growth are positively correlated, we reasoned that hazard should increase with declining annual increment. We therefore proposed that stands be managed for maximum wood production and harvested not later than the intersection of current annual increment (CAI) and mean annual increment (MAI) (Safranyik et al. 1974). The purpose of this study was to test the validity of this proposal.

The first stage in validating our hazard-rating system was a historical review of outbreaks in British Columbia and Alberta. Outbreaks have occurred repeatedly in zones of high hazard, as we defined them on the basis of climate, and more importantly outbreaks in low-hazard areas have coincided with periods when climate was more favorable for the beetles (Safranyik et al. 1974).

The size threshold for stands to support an MPB outbreak, 20 cm minimum average diameter, has been validated by a number of investigators (Amman et al. 1977, Safranyik et al. 1975). The other aspect in our assessment of stand hazard is the definition of the time when physiological maturity is reached as defined by the intersection of CAI and MAI. Evidence for the validity of physiological maturity in hazard rating is presented herein.

Forest managers have experienced two problems in the application of our size-based hazard-rating system. First, the system does not satisfy the requirements of all wood producers, especially those who require large-diameter trees. Second, in the course of stand development, this type of hazard-rating system defines a threshold when proneness to MPB begins, but there is no definition of periods of hazard after that threshold has been exceeded. The system, therefore, defines the time when surveillance for MPB must commence but does not pinpoint the specific periods when an outbreak is likely to develop.

In this paper, we present the first of a series of volume growth measurements from lodgepole pine stands sustaining MPB outbreaks. We measured the trees most likely to be killed by the beetles, dominants and codominants. We derived growth curves for the trees to determine how near they are to physiological maturity.

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METHODS

Twelve dominant and codominant lodgepole pine were cut in spring of 1978 from the center of a grove in a lodgepole-aspen parkland near Riske Creek, British Columbia. Four of these trees had been attacked in 1977. An MPB outbreak had started in this parkland about 1972 and has been spreading since that time. In the grove sampled, two trees were attacked and killed in 1976 and eight in 1977.

Eleven discs were cut at intervals over the height of each stem. Two average radii were located on each disc and the incremental growth along each radius measured. Detailed procedures and programs used to compute growth are described in Thomson and Van Sickle (1980).

Stand age was estimated from single increment cores and outside bark diameters measured at 1.3 m from 50-tree samples in two other groves in the parkland about 1 km and 4 km away, as well as from the sample trees.

STAND HAZARD TO MPB

Riske Creek is in the moderate risk zone in terms of climate suitability for the beetle (Safranyik et al. 1975). Stand hazard in this area was defined according to criteria in Safranyik et al. (1975) using the site classification on the B.C. Ministry of Forests forest cover maps and yield tables such as published by Smithers (1961). With average stocking, stands on the parkland surrounding Riske Creek should reach 20 cm average diameter between 80 and 90 years of age and the current and mean annual increment curves should intersect about age 100. With the indicated stand age of 106 ± 8.8 years in 1977 on the basis of the 12 trees cut, and 96 ± 11.3 and 99 ± 9.5 years at 1.3 m from the two 50-tree samples, an outbreak could have been expected after about 1962 (stand age about 85). Average diameters at approximately age 100 from these three samples are 27.0 cm, 29.1 cm, and 26.5 cm, respectively. Hence the stands near Riske Creek can be defined as entering the period of proneness to MPB in the mid-1960's and reaching physiological maturity about 1977. Hazard based upon minimum size gives about a 10-year warning period, but physiological maturity for the stand has coincided with outbreak rather than preceding it.

Physiological maturity is defined from volume curves developed for stands as a whole. The decline in CAI prior to intersection with MAI is due to the death of individual trees in the stand as well as to a gradual decline in height and radial increments as trees age. Hence, the condition of individual trees is not necessarily indicated by the stand curves. We, therefore, calculated growth curves for individual trees most likely to be attacked, the dominants and codominants, to see whether growth of these trees had given warning of the outbreak.

Physiological Maturity of Individual Trees and Stand Hazard

The general form of the relationship of tree volume to tree age is an initial period of slow rise, followed by a period of rapid increase in volume with age, with tree volume finally approaching an asymptote (Reed 1980). This description can be approximated by a logistic curve:

$$\text{volume} = a/(1 + e^{b+c\cdot \text{age}}) \qquad (1)$$

The relationship of current annual increment of the tree (CAI) to tree age is defined by the derivative of equation (1):

$$\text{CAI} = -\frac{ace^{b+c\cdot \text{age}}}{(1 + e^{b+c\cdot \text{age}})^2}$$

Figure 1 shows the relationship of both CAI and mean annual increment (MAI) of three trees from the Riske Creek sample. Curves fitted to the CAI from age 20 by equation (2), using Marquardt's algorithm for nonlinear regression, are also indicated. Seven of the 12 stems are in the decline phase of rate of volume accretion and are approaching intersection with MAI. An example is given in figure 1a. Three trees, however, are still growing at their maximum rate (see fig. 1b). In two trees the growth pattern was so erratic that the flat curve fitted to the CAI was not significant (see fig. 1c). The r^2 value of observed to predicted was 0.82, .43, and .18 for trees illustrated in figures 1a, b, and c, respectively.

The seven trees with declining growth rates are near the point of intersection of CAI and MAI. In the two trees with fitted curves illustrated in figure 1c, CAI and MAI had intersected. Hence, nine of the 12 trees in the sample from this outbreak are at or are rapidly approaching physiological maturity.

Stand Diameter and Hazard from MPB

The relationship between diameter at 1.3 m and age for each of the 12 trees is given in figure 2. The dotted horizontal line indicates the inside bark measurement equivalent to 24.3 cm (10 in) d.b.h.o.b. on this site. In trees greater than 24.3

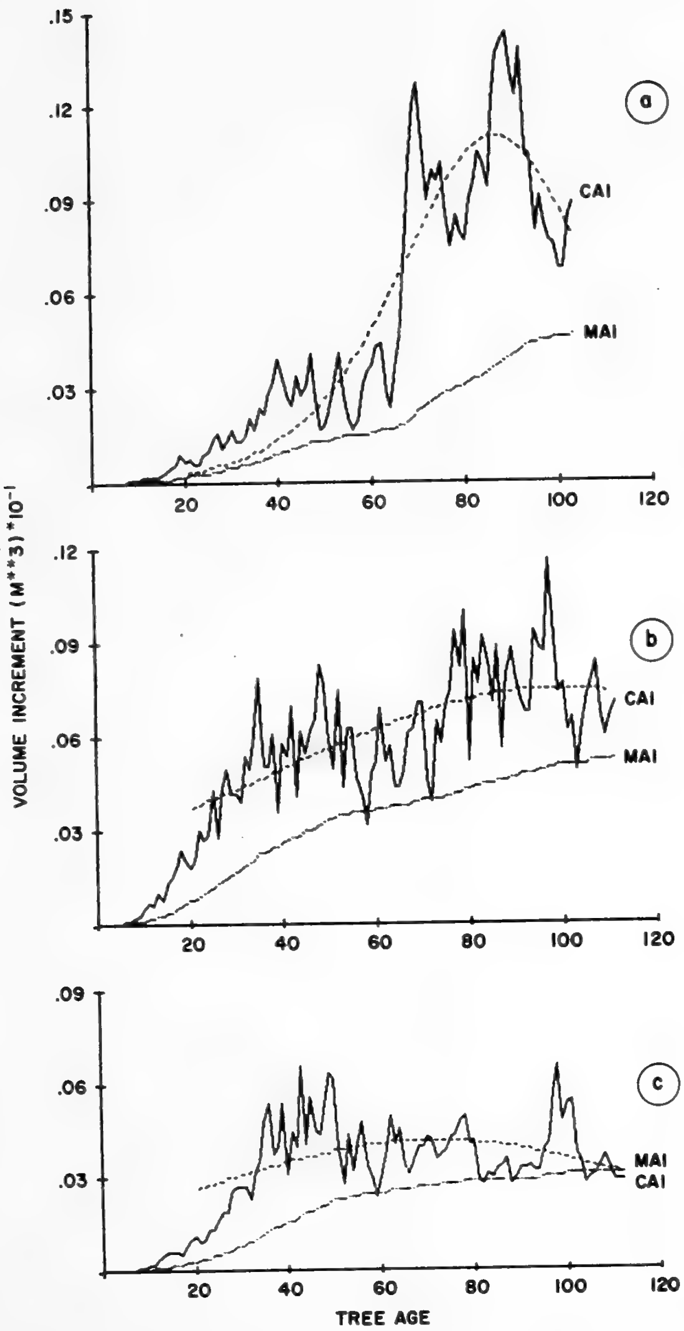

Figure 1.--The relationship between observed (solid line), calculated annual increment, mean annual increment, and age for lodgepole pine at Riske Creek, B.C.

cm d.b.h.o.b., a greater number of brood is produced than the number of beetles that attack; and therefore an increase in population occurs (Safranyik et al. 1975).

At the time of cutting, nine of the 12 trees were 24.3 cm in diameter or greater. One tree has been greater than 24.3 cm for 38 years, another for 28 years, and four additional trees have exceeded 24.3 cm since 1971, which was the beginning of the outbreak. The outbreak has therefore been sustained from the time when about half of the stems began to exceed the diameter when a yearly increase in the MPB population is possible. Average diameters of the two 50-tree samples--26.5 and 29.1 cm--would suggest that this conclusion can be applied to the parkland in general.

Periodic Growth Ratio and Hazard to MPB

Periodic growth ratio (PGR) has been suggested as a method of assessing hazard of lodgepole pine stands from MPB. The method was evaluated for 21 stands with considerable success (Mahoney 1978). A ratio less than 1.0 was used to define hazard. On a theoretical basis, however, the use of this ratio would not appear sound.

Growth in radial increment is at a maximum when the tree is about 20 to 30 years old and afterward tends to decline (Duff and Nolan 1953). On average, therefore, PGR should tend to decline after about 30 years. A ratio greater than 1 would be the result of release, or periods of above-average rainfall. But most of the time, after the trees reach ca. age 30, the ratio should be less than 1.0.

Periodic growth ratios were calculated for the 1.3-m disc for the 12 trees from 10 years of age to the year of cutting. After the trees reached about 20 years of age, most ratios were less than 1. Ratios greater than 1 do occur briefly, and interestingly PGR was greater than 1 for seven of the 12 trees in the last 2 years of growth, when trees were being attacked in this grove.

Volume Increment and Hazard to MPB

Although volume growth rate was variable over the lifetime of the trees, all of the 12 trees show a large decline in rate of volume incremental growth between 1970 and 1973 (fig. 1). Because of the erratic growth pattern, we cannot say at

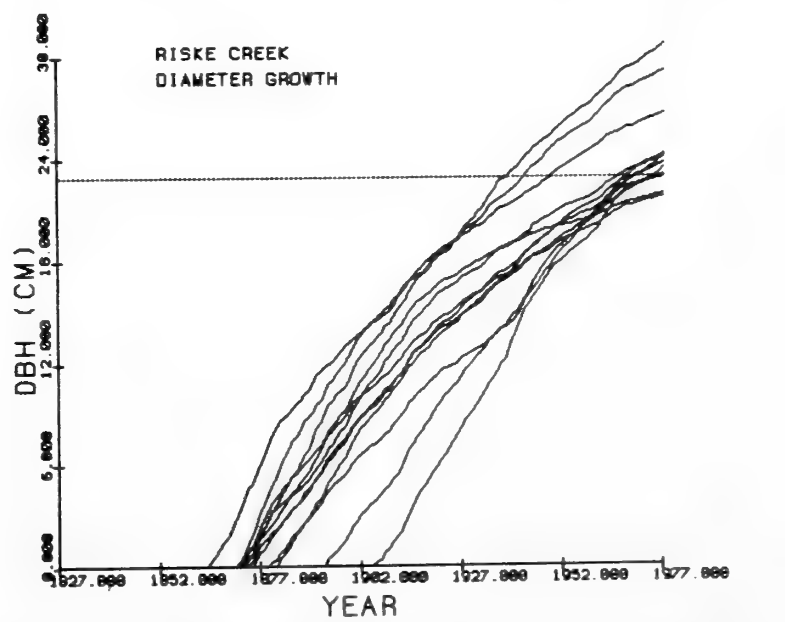

Figure 2.--The relationship between cumulative diameter and age for 12 lodgepole pine at Riske Creek, B.C. The dotted horizontal line indicates 24.3 cm d.b.h.o.b.

this time whether there is anything unique about this particular decline in growth or of use in hazard rating. The growth collapse, on the other hand, is coincident with the beginnings of the outbreak. This would suggest that trees were responding to a stress and the outbreak may have resulted.

We are currently comparing growth profiles during this period of decreased growth with profiles from earlier declines in growth to see if there is anything unique about this last decline. We are also doing correlations with weather records.

If this form of growth collapse is coincident with the start of outbreaks in the other five plots, a means of assessing hazard after the stands have entered the period of proneness to MPB may be possible.

Potential Volume Loss from MPB

Potential volume growth of trees most commonly killed by the MPB, the dominants and codominants, is an important consideration in determining what action to take in response to the beetle. Volume growth of the 12 trees was projected for 10 years using the fitted logistic curves derivative illustrated in figure 1. Current volume, projected volume, and the percentage increases are given in table 1.

All trees are at or beyond the point of maximum growth rate; however, the projected increase in volume for the 10-year period is a minimum of 8 percent and maximum of 18 percent. The average increase for the 12 trees is 12 percent. The total potential increase in volume for the 12 trees is 0.68 m^3.

Table 1.--Projected 10-year increase in volume for 12 lodgepole pines at Riske Creek, B.C.

Tree	Volume when cut (m^3)	10-Year growth projection	Percent increase
1	.3040	.3349	10.16
2	.4010	.4432	10.54
3	.3480	.3758	7.98
4	.4190	.4670	11.45
5	.6910	.7508	8.66
6	.4920	.5499	11.76
7	.7360	.8476	15.16
8	.5830	.6551	12.36
9	.4450	.5081	14.19
10	.4820	.5404	12.12
11	.4560	.5367	17.69
12	.3450	.3833	11.10

Average projected percent increase 11.93% ± 2.71.

CONCLUSIONS

Potential volume loss from the MPB is significant over a 10-year period if, on average, stands are cropped by the beetle at approximately the same stage of maturity as the Riske Creek stand. The projected 10-year increase in volume of the 12 trees is about equal to an additional 1.5 trees.

Available data for the Riske Creek stand indicate that the average diameter has been greater than 20 cm for about 15 years. Our analysis of diameter in relation to age suggests that about half the stems have been greater than 24.2 cm since the outbreak commenced. These values are again emphasized in determining whether a stand is prone to an outbreak. The outbreak in the Riske Creek stand has coincided with physiological maturity of the stand, and most trees sampled are in the period of declining volume growth. Periodic growth ratios less than 1 have also coincided with this outbreak, but ratios greater than 1 occurred in 7 of the 12 trees for 2 years prior to attack. None of these values, however, has predicted the onset of the outbreak with better than 5 to 10 years' accuracy.

At the present we can define when a stand becomes prone to outbreak but still cannot define when that outbreak may commence.

LITERATURE CITED

Amman, G. D., M. D. McGregor, D. B. Cahill, and W. H. Klein. 1977. Guidelines for reducing losses of lodgepole pine to the mountain pine beetle in unmanaged stands in the Rocky Mountains. 19 p. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. INT-36. Intermountain For. Range Exp. Stn., Ogden, Utah.

Duff, G. H., and N. J. Nolan. 1953. Growth and morphogensis in the Canadian forest species. I. The controls of cambial and apical activity in *Pinus resinosa* Ait. Can. J. Bot. 31: 471-513.

Mahoney, R. L. 1978. Lodgepole pine/ mountain pine beetle risk classification methods and their application. *In* Theory and practice of mountain pine beetle management in lodgepole pine forests. p. 106-113. A. A. Berryman, G. D. Amman, and R. W. Stark, eds. Forest Wildlife and Range Exp. Stn., University of Idaho, Moscow.

Reed, K. L. 1980. An ecological approach to modeling growth of forest trees. For. Sci. 26:33-50.

Safranyik, L., D. M. Shrimpton, and H. S. Whitney. 1974. Management of lodgepole pine to reduce losses from the mountain pine beetle. 24 p. Can. For. Serv., For. Tech. Rept. 1. Victoria, B.C.

Safranyik, L., D. M. Shrimpton, and H. S. Whitney. 1975. An interpretation of the interaction between lodgepole pine, the mountain pine beetle, and its associated blue stain fungi in Western Canada. *In* Management of lodgepole pine ecosystems. p. 406-428. D. M. Baumgartner, ed. Washington State Univ., Coop. Ext. Serv., Pullman.

Smithers, L. A. 1971. Lodgepole pine in Alberta. 153 p. Can. Dep. Forestry, Bull. 127.

Thomson, A. J., and A. Van Sickle. 1980. Estimation of tree growth losses caused by pest activity. Can. J. For. Res. 10:176-182.

HAZARD RATING FOR MORTALITY CAUSED BY THE FIR ENGRAVER AND THE MOUNTAIN PINE BEETLE IN THE NORTHERN ROCKY MOUNTAINS

James A. Moore, Ronald L. Mahoney, and John A. Schenk[1]

HAZARD RATING GRAND FIR STANDS FOR THE FIR ENGRAVER

Expected Users of the System

Stands of grand fir, *Abies grandis* (Dougl.) Lindl., potentially susceptible to mortality caused by the fir engraver, *Scolytus ventralis* (LeConte), need to be identified early so that silvicultural treatments can be successfully applied to reduce losses. Development of a hazard rating useful to forest managers should be based on easily obtained inventory data. Furthermore, it is desirable to express the stand hazard using variables that forest managers can alter through silvicultural practices. These factors were important considerations in selecting variables during model development.

Stand susceptibility was hypothesized to be a function of stand density and host tree availability (purity). The reader is referred to Schenk et al. (1977) for details on methods, analyses and results.

Expected Use in Management Planning

The hazard rating showed a strong correlation with fir engraver-caused grand fir mortality and provided useful information to forest managers. The hazard rating can be used in two ways. For the short term (3 to 5 years) stand hazard can be computed from current inventory data. This information would be only one among numerous other factors managers must consider in scheduling management activities but may be crucial to an accurate prediction of management consequences. For example, harvesting priorities may be determined such that a stand expected to sustain high fir-engraver mortality could be cut before a stand with lower hazard. The second or long-term potential use for the system is in conjunction with a stand simulation model such as the prognosis model by Stage (1973). Using existing simulation techniques, managers may project a stand through time, and by computing the hazard value at intervals during the projection, periodically identify those stands most likely to sustain unacceptable losses to the fir engraver. Because the hazard rating uses variables (density and species composition) that can be manipulated through silvicultural practices, it provides a rather direct procedure to evaluate the consequences of alternative silvicultural regimes in terms of the likelihood of future fir engraver-caused grand fir mortality.

Validation of the System

Moore et al. (1978) tested the equations on an independent data set consisting of eight additional grand fir stands, and readers are directed to that paper for details. The model was not shown to be invalid. The validation process provides confidence that the hazard rating is useful for forest management planning concerning the relative susceptibility of grand fir stands to fir engraver-caused tree mortality.

Problems Encountered

The hazard rating is intentionally simple so that it can be compiled from inventory data and is based on only stand (tree) characteristics. Thus, it does not include any information about other factors, such as site conditions, pathogenic influences, beetle population dynamics, etc., that may be important in determining the susceptibility for a given stand. Sometimes these limitations result in decreased accuracy of prediction. For example, during model validation one stand had a considerably lower predicted than observed mortality. In this stand approximately 40 percent of the area consisted of rootrot pockets, and most of the grand fir within and bordering these infection centers were severely impacted by root pathogens. The hazard rating was developed in stands where root-rot pockets comprised less than 15 percent of the area, and the mortality estimates derived from the equations were valid for this range of root-rot infection. However, when the model is applied to severely infected stands, mortality levels likely will be underestimated.

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Similarly, the hazard rating should not be applied to other conditions differing from those where it was developed. Obviously this caution applies to all models, but it is especially important in this instance for not only the mathematical limitations but for biological reasons as well. The hazard rating should be applied only to grand fir-dominated stands with an average d.b.h. greater than 6 inches (15.2 cm). A grand fir-dominated stand is defined as one whose sum of diameters for grand fir used in the equation for calculating Diversity Index (Brillouin 1962) is numerically larger than that for any other individual tree species (i.e., a plurality of grand fir). While these are not overly restrictive specifications, they are important and should be observed when using the hazard-rating system.

Retrospective Modifications

If we were to repeat the study, we would change the method used to monitor tree mortality in the study stands. In this study, the stands were sampled using randomly located grids of permanent plots. The plots were established at the beginning of the mortality assessment period and were revisited at least annually to record any mortality of the permanently marked plot trees. While this was a very accurate method to estimate mortality over the 3-year period, it was also very time consuming, and therefore limited the number of test stands. A more efficient sampling procedure would have been to sample more stands with temporary plots and estimate past mortality for the most recent 3-year period.

HAZARD RATING LODGEPOLE PINE STANDS FOR MOUNTAIN PINE BEETLE

Expected Users of the System

An approach similar to the fir engraver hazard rating was developed for the lodgepole pine (*Pinus contorta* Dougl. var *latifolia* Engelm.)/mountain pine beetle (*Dendroctonus ponderosae* Hopkins) system. Because lodgepole pine exists mainly in large, pure stands, it is even more critical that potentially susceptible stands be identified well before an outbreak if silvicultural treatments are to be successful in reducing losses due to mountain pine beetle.

The hazard rating is intended to be used directly by forest managers; therefore, a similar rationale was used to formulate the mountain pine beetle hazard rating as for the fir engraver. Stand susceptibility was hypothesized to be a function of stand density and purity. The hazard-rating system was originally developed from data collected in 11 lodgepole pole pine stands in central Idaho. The following is the form of the hazard-rating equation:

$$Y = a + b \times e^{X} \qquad [1]$$

where

Y = percent of lodgepole pine trees per acre in a 7-year period

e = Base of the natural logarithms

X = an interaction of stand density and species composition (Stand density × proportion lodgepole pine basal area)

Stand density was expressed by Crown Competition Factor (Krajicek et al. 1961). The model expresses an interaction of density (competitive stress) and host availability such that the highest hazard values will be computed from pure, dense lodgepole stands. The statistical fit of the model to the central Idaho data was very good ($r^2 = .89$ and a standard error of estimate of 9 percent of the mean of the dependent variable).

Expected Use in Management Planning

We expected that the hazard rating could be computed for the short term from mature (> 60 years) lodgepole stands and thus provide additional information for the manager to consider in scheduling harvest activities. However, a more important application would be in conjunction with stand projection techniques. Intermediate silvicultural treatments, especially thinning, could be evaluated in terms of reducing future losses to the mountain pine beetle. The preventive nature of a silvicultural regime should be stressed in lodgepole pine stands because treatments need to be applied before the trees are in such poor condition that the residual stand is unable to respond to the treatment. Thus, in unmanaged lodgepole pine stands greater than 60 yeras old, thinnings may reduce the hazard rating value but not correspondingly reduce the actual hazard of the stand to mountain pine beetle infestation.

Validation of the System

The hazard-rating system developed in central Idaho was tested in 10 lodgepole pine stands located in western Montana. The results of that test are presented in table 1 and figure 1.

Seven of the 10 observed mortality levels fell within the 95 percent confidence intervals constructed about the pre-

dicted values obtained using equations developed in central Idaho. It should be noted that the predicted values are generally lower than the observed values, suggesting regional differences in the relationships. This is supported by a test of the variance about the slopes and intercepts estimated for equation [1] from the Idaho and Montana data sets. There was no significant difference between the slopes, but the intercepts were significantly different. Thus, for a given hazard value, central Idaho had a greater percent of trees killed than Montana. However, the proportionate increase in mortality for increasing hazard values was similar for both areas. Regional differences are not unexpected and can be accounted for by analytical procedures. The general approach to the hazard rating seems applicable to both geographic areas, though.

Table 1.--Observed levels of lodgepole pine mortality by mountain pine beetle in western Montana v. mortality levels predicted by equation (2) developed from central Idaho data (fig. 1).

Stand hazard rating	Percent basal area killed Observed	Predicted
1.86	49	76
1.73	60	61
1.48	37	37
1.44	35	34
1.36	61	27
0.90	32	0
0.84	2	-3
0.75	9	-7
0.73	5	-8
0.66	18	-11

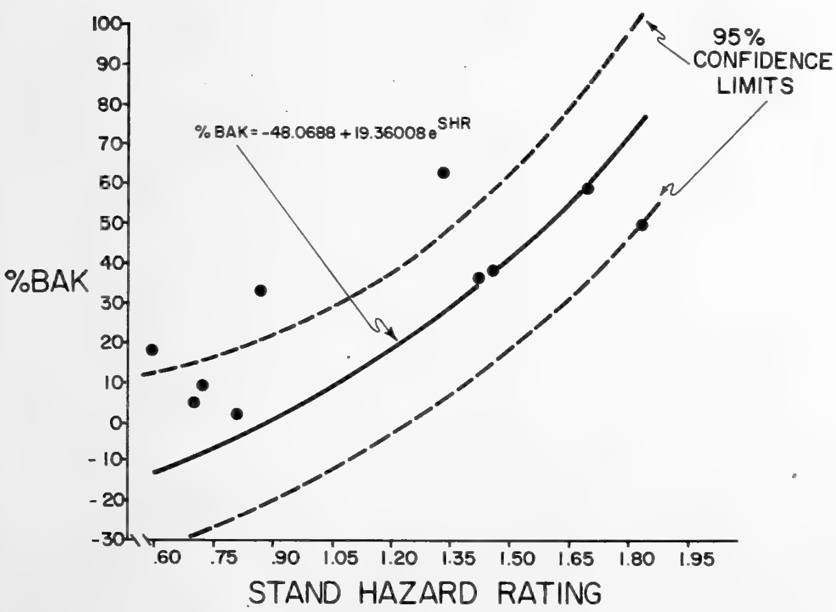

Figure 1.--Observed values for 10 western Montana lodgepole pine stands; a test of the risk classification method of Schenk et al. (1980).

Problems Encountered

This hazard rating is similar to that developed for the fir engraver in that both are based on only stand (tree) characteristics and can therefore be subject to the same problems. A more important problem encountered in developing a hazard rating for the lodgepole pine-mountain pine beetle interaction was the scarcity of managed lodgepole pine stands and the wide geographical and ecological amplitude of lodgepole pine. The system reported here was based on natural stands of varying density and species composition. It was desirable to include stands that had been under management for some time, but these stands are rare. The individual trees in dense, unmanaged lodgepole stands often have poor crowns and consequently the residual stand's response to thinning is nil or greatly delayed. We want to avoid the interpretation that thinning can immediately reduce the mountain pine beetle hazard in many unmanaged stands. Instead, the emphasis should be on maintenance of stand vigor throughout the rotation. That is, silvicultural treatments are preventive rather than curative measures.

Other Work Related to These Hazard-Rating Systems

Schenk et al. (1976) and Mahoney et al. (1979) examined the influence of site differences, as expressed by understory indicator plants, on grand fir stand susceptibility to fir engraver-caused mortality. These studies showed that plant groups indicative of dry sites were associated with high levels of fir engraver-caused mortality, and plant groups indicative of more favorable moisture conditions were associated with low levels of grand fir mortality by the fir engraver. Mahoney (1977) studied the periodic growth ratio, a measure of the current vigor trend of lodgepole pine stands, in endemic and epidemic mountain pine beetle infestations and found that stands with declining vigor were significantly more likely to sustain losses to the mountain pine beetle than stands with increasing or steady vigor trends.

Mahoney (1978) presented a comprehensive review of four mountain pine beetle risk classification methods. He applied each of the methods to the same case study stands and contrasted the results. He concluded that a combination of methods which rate the suitability of the environment for beetle population and methods which rate the susceptibility of stands to beetle-caused mortality is desirable to provide the best prediction of the mortality hazard.

LITERATURE CITED

Brillouin, L. 1962. Science and information theory. 2nd ed. 351 p. Academic Press, New York.

Krajicek, J. E., K. A. Brinkman, and S. F. Gingrich. 1961. Crown competition: a measure of density. For. Sci. 7: 35-42.

Mahoney, R. L. 1977. Classifying lodgepole pine stands as resistant or susceptible to mountain pine beetle. M. S. thesis, University of Idaho, Moscow. 28 p.

Mahoney, R. L. 1978. Lodgepole pine/ mountain pine beetle risk classification methods and their application. *In* Theory and practice of mountain pine beetle management in lodgepole pine forests: symposium proceedings. D. Kibbee, ed. p. 106-113. [Pullman, Wash., April 1978.] Forest, Wildlife and Range Exp. Stn., Univ. of Idaho, Moscow.

Mahoney, R. L., J. A. Moore, and J. A. Schenk. 1979. Validation and refinement of a plant indicator model for grand fir mortality by the fir engraver. J. Entomol. Soc. Brit. Columbia 76:17-19.

Moore, J. A., J. A. Schenk, and C. R. Hatch. 1978. Validation and refinement of a hazard rating model for fir engraver-caused mortality in grand fir stands. For. Sci. 24:309-312.

Schenk, J. A., R. L. Mahoney, and J. A. Moore. 1980. A model for hazard rating lodgepole pine stands for mortality by mountain pine beetle. For. Ecol. Manage. 3:57-68.

Schenk, J. A., R. L. Mahoney, J. A. Moore, and D. L. Adams. 1976. Understory plants as indicators of susceptibility of grand fir stands to *Scolytus ventralis* attack. J. Entomol. Soc. Brit. Columbia 73:21-24.

Schenk, J. A., J. A. Moore, D. L. Adams, and R. L. Mahoney. 1977. A preliminary hazard rating of grand fir stands for mortality by the fir engraver. For. Sci. 23:103-110.

Stage, A. R. 1973. Prognosis model for stand development. 32 p. U.S. Dep. Agric. For. Serv., Res. Pap. INT-137. Intermountain For. Range Exp. Stn., Ogden, Utah.

ESTIMATING FOREST STAND VULNERABILITY TO GYPSY MOTH

David A. Gansner[1]

Abstract.--This article traces the investigative steps that produced for forest pest management a risk-rating system aimed at gypsy moth control. Recent studies show that while most forest stands come through outbreaks with little or no tree loss, a few suffer heavy damage. Models for predicting stand losses have been developed and are now being tested and refined. These models make use of easy-to-measure key characteristics of stand condition such as tree vigor, species, elevation, tree size distribution, and position on slope.

People who have to make cost-effective decisions about controlling the gypsy moth need help in predicting and evaluating its impacts. How much forest damage will result from a particular gypsy moth outbreak? Which stands will suffer most? The answers depend on a number of interrelated factors such as the frequency and intensity of attack, the susceptibility of host trees, the effectiveness of control programs, and the influence of natural phenomena like predators and weather.

Since these factors are themselves difficult to predict, it is little wonder that we cannot accurately forecast impacts of the pest. But we can turn to recent experiences for some indication of what to expect. A typical gypsy moth outbreak occurred during the early 1970's in the Pocono Mountains of northeastern Pennsylvania. Field-plot data have given us measures of tree and timber losses associated with that infestation and have provided information needed to develop guides for estimating the amount of tree mortality and timber loss that could result from an outbreak.

BACKGROUND

Forest stand losses and stand characteristics were measured on 143 1/10-acre plots in Pike and Monroe Counties, Pennsylvania. This area was on the frontier of gypsy moth infestations in the early 1970's. The plots were established in 1971 in newly infested forest stands. Stand losses for trees 3 inches in diameter at breast height (d.b.h.) and larger were measured each year for 5 years. The stands were not sprayed to control the gypsy moth during the study period.

Severity and frequency of gypsy moth attacks varied from plot to plot. In general, the study area had moderate to heavy defoliation from 1971 through 1973. Insect populations all but collapsed in 1974 and 1975, and then built up again in 1976. Tree mortality reflected this pattern of infestation. Four-fifths of the losses recorded through 1976 accumulated from 1972 through 1974.

Selected plot variables provided a general description of the infested stands in 1971:

	Mean	Range
Basal area per acre (ft^2)	95	35-180
Percent of BA in oak	56	0-100
Average d.b.h. (in)	7.0	4.7-10.8
Stand age (yr)	68	25-105
Site index (ft, upland oaks)	59	30-80
Elevation (ft)	1190	620-1560
Standing timber value per acre ($)	132	20-840

Conversion standards developed by Mendel et al. (1976) were used to estimate the value of timber lost on each plot. These value standards incorporate species, d.b.h., butt log grade, and merchantable height for each tree.

EXTENT OF THE DAMAGE

Gansner and Herrick (1979) summarized forest stand losses by number of trees, basal area, timber volume, and value from 1972 through 1976 (figs. 1a-4b). It is immediately obvious that losses, however expressed, were not uniformly distributed among the plots. A small percentage of the infested stands incurred major losses while a large percentage of the stands incurred minor losses; that is, the distribution is skewed. For example, volume losses over the 5-year period averaged 2.5 cords per acre (fig. 3a). But 75 percent of the stands lost less than 2.5 cords per acre; 20 percent of the stands incurred no losses at all; and only 5 percent of the stands lost more than 10 cords per acre.

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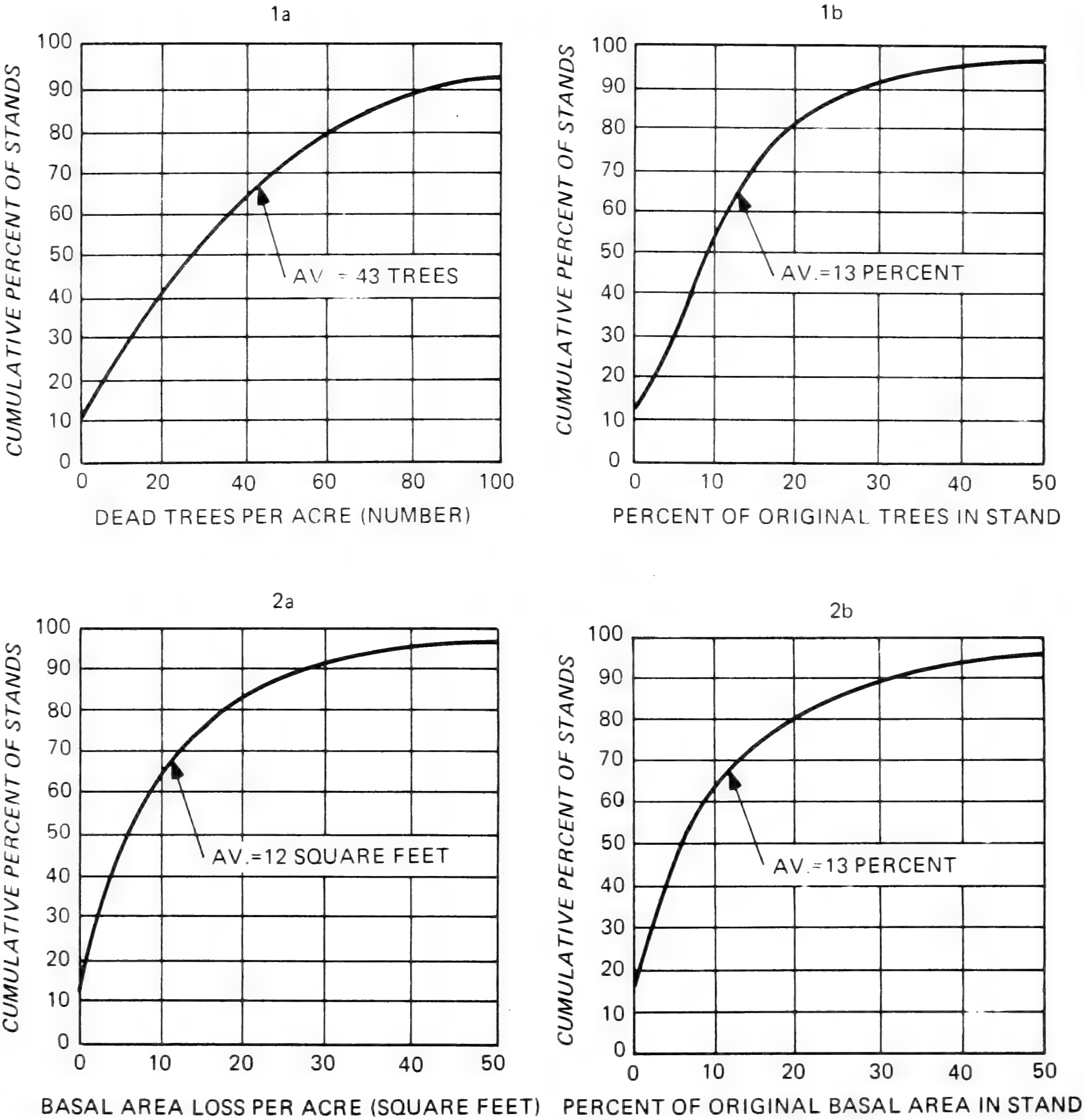

Figure 1a-2b.--Forest losses in gypsy moth-infested stands in the Poconos, 1972-76.

The frequency distributions of stand losses are highly skewed. In a skewed distribution the median (the value that divides the range of values into two equal parts) helps describe the "typical situation." Medians for the 5-year stand losses are

30 trees per acre (10 percent of the original stand of trees)

6 ft^2 of basal area per acre (7 percent of the original basal area)

1 cord per acre (4 percent of the original volume)

$4 per acre (4 percent of the original value)

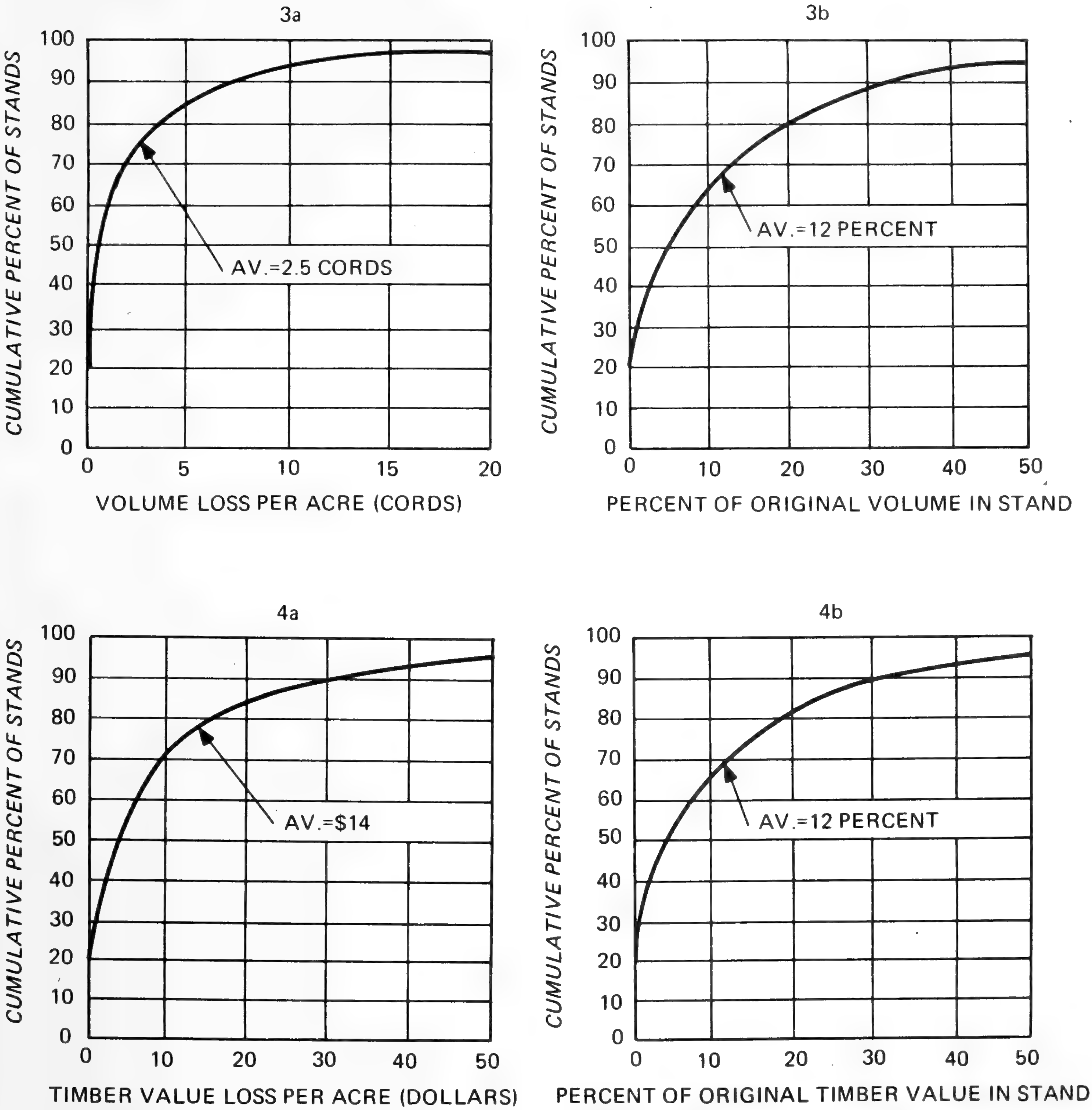

Figure 3a-4b.--Forest losses in gypsy moth-infested stands in the Poconos, 1972-76.

RATING STAND VULNERABILITY

Gansner et al. (1978) and Gansner and Herrick (1979) used two multiple variable techniques, stepwise regression and automatic interaction detection (AID), to develop guides for predicting stand vulnerability. Underlying the development of these models is the premise that tree mortality caused by the gypsy moth in any particular forest stand is related to and can therefore be expressed as a function of selected characteristics of that stand's condition.

We selected for analysis variables of forest stand condition thought to be good predictors of tree losses. These variables are measures of

Timber stand size composition
Average tree diameter
Timber stocking
Timber stand age
Species composition
Crown position
Crown condition
Site index
Land capability
Elevation
Aspect
Slope
Position on slope

We based the choice of these variables primarily on findings of Kegg (1971), Campbell and Sloan (1977), and Houston and Valentine (1977).

The Regression Models

Stepwise multiple regression analyses gave us two simple equations for rating the hazard (HR) of impending gypsy moth attacks to forest stands:

$$HRN = 11.85 + 0.82\ (NPC) + 0.0005\ (NWO)^2$$
$$R^2 = 0.73$$

$$HRP = 4.16 + 0.83\ (PPC) + 0.001\ (PWO)^2$$
$$R^2 = 0.57$$

where

HRN = number of trees per acre that will die

HRP = percentage of trees that will die

NPC = number of live trees per acre with poor crowns[2]

NWO = number of live trees per acre in the white oak species group

PPC = percentage of live trees with poor crowns

PWO = percentage of live trees in the white oak species group.

Only two of the many elements of stand condition analyzed as independent variables are included in these equations, and their inclusion makes good sense. *White oaks* are a preferred food of the gypsy moth and usually are attacked more severely than other tree species. Trees with *poor crowns* have low vigor and are more likely to die after defoliation.

[2] Crowns were classed as poor when 50 percent or more of the branches were dead (allowances permitted for nonselfpruning species); when foliage density, size, or coloration was of subnormal quality; or when epicormic sprouting was heavy.

The coefficient of multiple determination (R^2) for each equation is greater than 0.57. Thus, the relatively few independent variables in these equations explain a rather large share of the variation in tree mortality for the sample plots; the models fit the sample data well.

We checked the performance of the hazard-rating equations by applying them to the 143 sample plots used in this study. Tree loss estimated by the equations was compared with actual loss recorded on the plots. Each plot was assigned hazard ratings based on predicted estimates of tree loss as follows:

Tree mortality measure	Hazard rating class		
	Low	Moderate	High
Number per acre	<30	30-74.99	75+
Percent	<10	10-24.99	25+

Then we compared hazard ratings predicted by the equations with actual ratings recorded for the plots. Three-fourths of the ratings predicted for the plots agreed with actual outcomes. Very few of the predictions missed by more than one rating class. For example, less than 4 percent of the plots classified as low hazard actually turned out to be in high-hazard situations.

This exercise by no means represents an exhaustive test of model performance, but it does indicate the kind of results that users of the hazard-rating equations might expect.

The AID Models

The AID technique developed by Sonquist et al. (1973) produced slightly different results. In this case the dependent variables analyzed were percent of trees killed and percent of timber value lost.

AID partitions observations (plots in this study) through a series of two-way splits into a series of subgroups. Each plot is a member of one of the subgroups. The splits are so chosen that, at each step of the procedure, the two new groups will reduce the variance of the dependent variable more than any other pair of subgroups. Since each split is conditioned on a prior one, the model can detect and handle interaction effects as well as causal priorities.

Selection and partitioning of the set of predictor variables are optimal when the categories defined explain more

of the variation in the dependent variable than is possible with any other set of subgroups. Results are readily visualized as branching diagrams.

The AID analysis of *tree mortality* delineated nine mutually exclusive groups of plots and the proportion of loss in each group. Six variables defined the tree-loss classification system. Figure 5 shows the tree-loss profiles. Stands at elevations of 1,000 ft or higher and in which 20 percent or more of the trees had poor crowns before infestation (Group 9) had the highest mortality-42 percent, compared with 13 percent for the total sample. This group accounted for 6 percent of the sample.

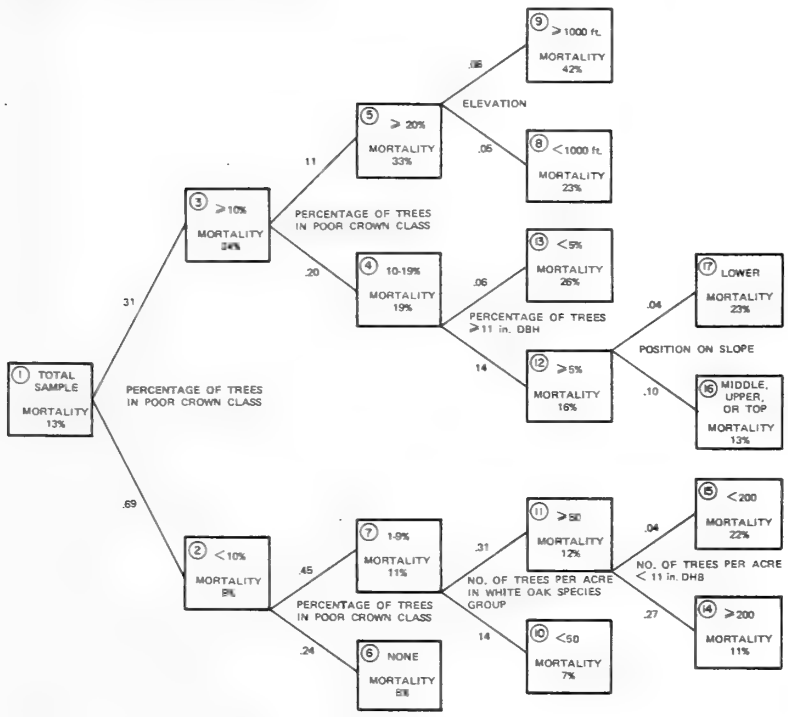

Figure 5.--Tree mortality variables. The average stand mortality is shown for each group. The decimal fraction on each leg shows the proportion of sample in that group.

Stands with the least tree loss (Group 6) were effectively identified by one characteristic: crown condition class. Thus, stands having no trees with poor crowns (24 percent of the sample) had only 5 percent mortality--one-eighth as much as in the highest mortality group. Similarly, intermediate groups, with tree mortality rates ranging from 7 to 26 percent, can be identified.

In some cases, *value loss* rather than tree loss may be the desirable basis for decisionmaking. Figure 6 presents the AID results expressed in percentage of stand value loss. Percentage of trees with poor crowns was the criterion that most sharply separated value loss. The crown condition and elevation combination that defined the highest tree mortality group also selects the group (Group 9) with the greatest timber value loss--51 percent, compared with the sample average of 12 percent.

Species, basal area, aspect, and site index were the other important predictors. Plots with the lowest value loss (3 percent) had 50 or more white oaks per acre, 40 ft^2 or more of basal area in trees 3 to 11 inches d.b.h., and less than 5 ft^2 of basal area in poor crown-condition trees; and they were not level or facing south or southwest (Group 14). Value loss for intermediate groups ranged from 5 to 32 percent.

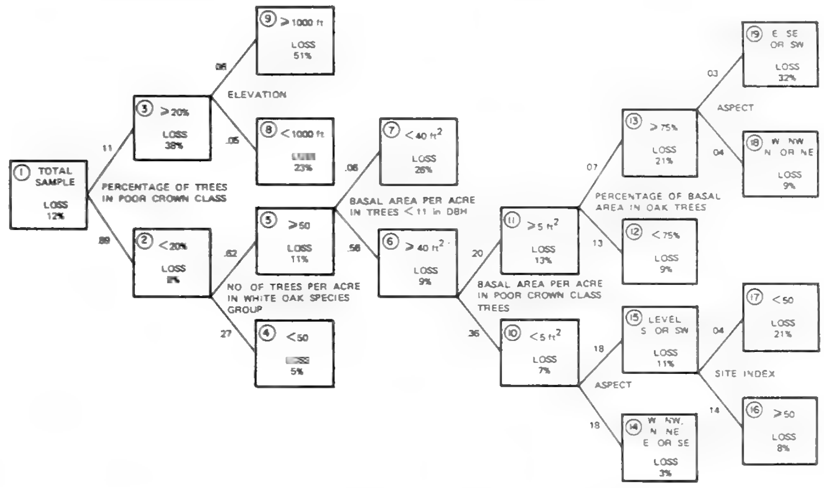

Figure 6.--Variables used to explain timber value losses. The average value loss is shown for each group. The decimal fraction on each leg shows the proportion of sample in that group.

IMPLICATIONS FOR MANAGEMENT

Knowing how much and what kind of damage to expect from gypsy moth outbreaks is a must for planners of cost-effective control programs. One 5-year case study of forest stand losses in the Poconos will not provide reliable and specific answers to all the questions about impacts of the insect. But it does give us fresh perspective on what, in general, to expect.

Only a small percentage of infested stands suffered major losses. This finding holds important implications for people whose job is to make cost-effective decisions about control. Suppose, for example, that effective gypsy moth control in infested stands required three successive annual treatments, each costing $10 per acre-that is, a total outlay of $30 per acre. Our analysis indicates that without treatment, 90 percent of the infested stands would suffer timber value losses of less than $30 per acre (fig. 4a). So, from the standpoint of timber value saved, the cost of the treatment would be justified on only 10 percent of the infested stands.

The scenario for a 1,000,000-acre outbreak is depicted in figure 7. If stands with the largest value loss were treated first, at the economic optimum:

You would treat 100,000 acres.
Program cost = $3,000,000
Value saved = Benefit = $8,500,000
Benefit/Cost = 8.5/3 = 2.8
You would still lose $5,000,000

But, program cost plus loss would be minimized--$3,000,000 + $5,000,000 = $8,000,000.

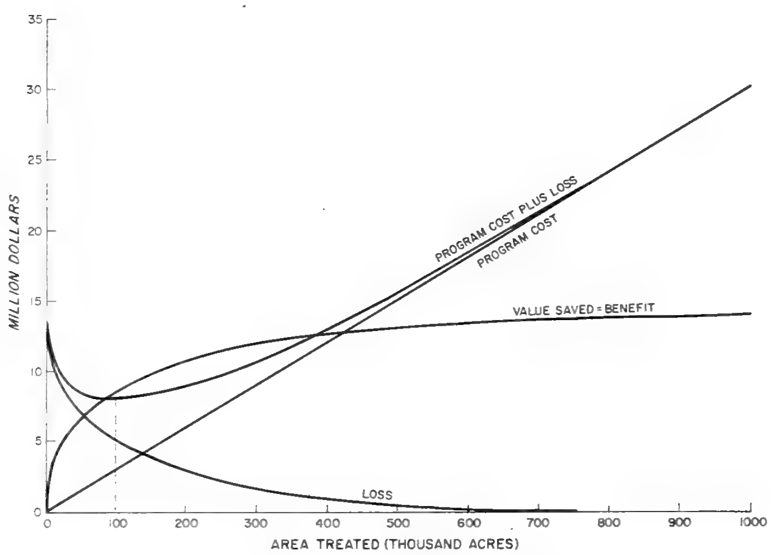

Figure 7.--Treatment scenario for an outbreak of 1,000,000 acres.

Of course, decisions on gypsy moth control are based on more than the value of timber losses. Changes in stand condition and timber growth should be considered. Also important are nontimber impacts on esthetic quality and the nuisance of caterpillars in recreation areas and backyards.

Moreover, an operational decision-making model must be able to help us determine not only how many forest stands to protect but also which ones. And it must be able to provide this information before the insect attacks.

Techniques have been developed for predicting forest stand losses attributed to the gypsy moth. They can be used to estimate losses from easy-to-measure key characteristics of stand condition. These models must be used cautiously and with due regard for their limitations. As they have not been field tested, we do not know how well they would apply on a new frontier of infestation. Plans have been made to test them.

Despite the problems, our findings offer information for decisionmaking, particularly where tree and timber volume and value losses are considered important. Control decisions about the gypsy moth are being made every year, often based on experience and intuition alone. Results of this analysis should add a bit more objectivity to the process.

LITERATURE CITED

Campbell, R. W., and R. J. Sloan. 1977. Forest stand responses to defoliation by the gypsy moth. 34 p. For. Sci. Monogr. 19.

Gansner, D. A., and O. W. Herrick. 1979. Forest stand losses to gypsy moth in the Poconos. 5 p. U.S. Dep. Agric. For. Serv., Res. Note NE-273. Northeast For. Exp. Stn., Broomall, Penna.

Gansner, D. A., O. W. Herrick, and W. B. White. 1978. Economic analysis of the gypsy moth problem in the Northeast. IV. Forest stand hazard ratings for gypsy moth. 3 p. U.S. Dep. Agric. For. Serv., Res. Pap. NE-410. Northeast. For. Exp. Stn., Broomall, Penna.

Herrick, O. W., D. A. Gansner, and P. S. DeBald. 1979. Predicting stand losses from the gypsy moth: an application of automatic interaction detection (AID). J. For. 77(2):91-94.

Houston, D. R., and H. T. Valentine. 1977. Comparing and predicting forest stand susceptibility to gypsy moth. Can. J. For. Res. 7(3):447-461.

Kegg, J. D. 1971. The impact of the gypsy moth: repeated defoliation of oak in New Jersey. J. For. 69:852-854.

Mendel, J. J., P. S. DeBald, and M. E. Dale. 1976. Tree value conversion standards for hardwood sawtimber. SETs: stand evaluation tools 2. 74 p. U.S. Dep. Agric. For. Serv., Res. Pap. NE-337. Northeast. For. Exp. Stn., Broomall, Penna.

Sonquist, J. A., E. Lauh Baker, and J. N. Morgan. 1973. Searching for structure. 236 p. Survey Res. Cent. Inst. Soc. Res., University of Michigan, Ann Arbor.

DAMAGE SUSCEPTIBILITY RATINGS AS A CATALYST TO COST-EFFECTIVE FOREST PEST MANAGEMENT

Owen W. Herrick[1]

Abstract.--This paper traces the merger of forest damage susceptibility rating and economic theory to a decision framework for forest pest management aimed at gypsy moth control. For efficient forest pest management, the size and intensity of outbreak, subsequent physical and economic impacts, and the cost of control need to be considered jointly as a system. A model indicates the optimal degree of pest management (acreage to be treated) and the optimal dollars to be spent on control. The model also identifies a pest control strategy that gives priority to the kind and amount of forest land where treatment could do most to avert damage in the planning unit.

A recent pamphlet on integrated pest management (IPM) contains the statement that "risk rating. . . is one technique used in preventing mountain pine beetle epidemics" (USDA Forest Service 1980). But how risk rating prevents a forest pest epidemic is not clear, because risk rating alone cannot prevent epidemics.

This statement does not deny the value of risk-rating systems; they are, in fact, a key item--a catalyst--in making cost-effective pest management plans. The topic for our attention is the link between risk rating and cost-effective prescriptions for forest pest management action.

BACKGROUND PERSPECTIVES

The general context relates to controlling forest defoliators. All data are from the gypsy moth outbreak of the early 1970's in the Pocono region of Pennsylvania.

Initial work focused on impact distributions that showed forest stand damages are highly skewed: a small percent of infested stands incurred major losses while a large percent had minor losses (Gansner and Herrick 1979). Unevenly distributed stand damage supports the development of rating systems, the underlying notion being that cost-effective control programs need to be based on recognition of how much and where (in what kinds of stands) damage is likely to occur.

The basic premise in our hazard-rating scheme was that gypsy moth damage in any particular forest stand is related to the stand's condition, and therefore, can be expressed as a function of selected characteristics reflecting stand condition. Much of the rationale for this thesis is presented in Campbell and Sloan (1977). Measures of preoutbreak forest stand conditions were used to establish baseline information for characterizing the stands and subsequently assessing postoutbreak damages. We included variables that (1) are easy-to-measure stand characteristics thought to correlate with the severity of damage, and (2) can be used in a predictive sense.

Automatic interaction detection (AID) was used to develop a damage susceptibility rating model with impact data as the dependent variable and preoutbreak stand condition parameters as independent variables (Herrick et al. 1979). The AID method isolates mutually exclusive groups of stand conditions and identifies the corresponding impact in each group. Depending on the group and its member stands, timber value loss, for example, ranged from 3 to 51 percent.

DEVELOPING A FRAMEWORK FOR DECISIONS

Forest pest management ultimately reduces impact rather than produces a physical product. Thus, pest management costs should be balanced against impact reduction. What follows is a review of an adaptation of cost-plus-loss economic theory that illustrates the use of incremental analysis as one way to pursue maximum effectiveness vis-à-vis investment in forest pest management (Herrick 1981).

Damage Function

The identification of susceptibility classes (by AID, for example) provides a basis for predicting stand losses that can be used collectively to quantify

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physical and economic impacts and specify a damage function for a planning unit. We obtained the damage function for a 100,000-acre planning unit by arranging forest stand group values from least to most loss. When plotted, the damage function traces cumulative timber value loss corresponding to the cumulative percent reduction in the flow of product from the unit (fig. 1).

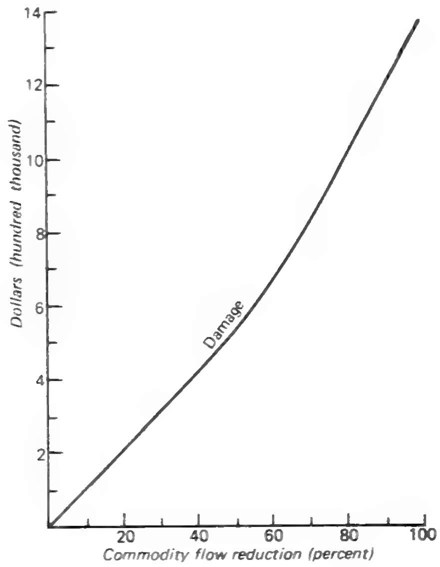

Figure 1.--Damage function--timber value loss related to levels of commodity flow.

Similar estimates of potential losses in other planning units could be obtained by classifying the unit's stand conditions based on key characteristics from the susceptibility rating model. Any scheme that gives estimates of potential loss and its area distribution within the planning unit gives the essential information for a damage function.

Intensity Function

The classification of potential losses also establishes the relationship between the area that might be infested and its likely impact on flow of product from the planning unit. This "intensity function" indicates the cumulative impact on the flow of product for each additional unit of acreage infested. For convenience, it can be plotted below the damage function using the same horizontal axis for product flow reduction (in percent) and a vertical axis extending down from the origin for acreage (fig. 2).

The diagram now relates potential losses in product flow to planning unit area (intensity function) and to value loss (damage function). These are impacts of infestation.

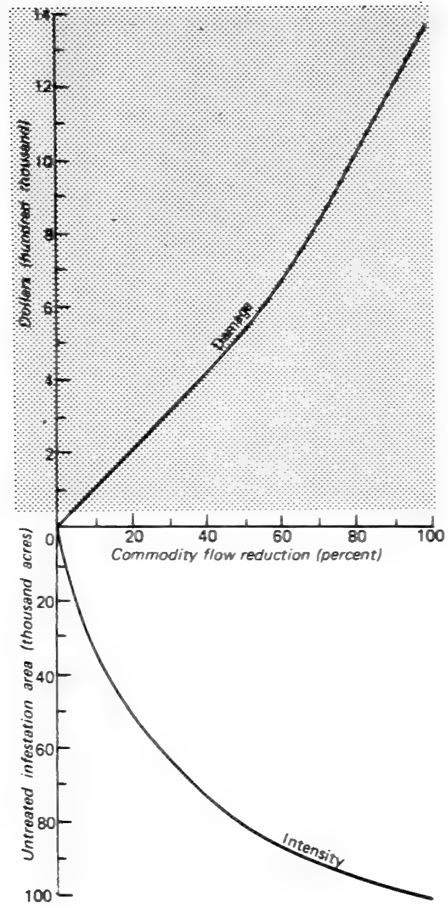

Figure 2.--Intensity function--relationship between area infested and insect-induced reduction in commodity flow.

Cost Function

If forest pest management is to control these impacts (at some level), it will entail a cost. In the gypsy moth example, cost records of cooperative gypsy moth control programs in the Northeastern States were used. We identified an efficient frontier of operating plans from among those previously applied by plotting the relationship between each program's cost and area treated. This trace of cost-efficient projects provides a cost function that is plotted beside the damage function with dollars on the vertical axis and treatment area extending left from the origin (fig. 3).

The combined diagram now shows the relationship among untreated infestation area, intensity, physical effects, dollar damages, size of treatment area, and costs. To tie these relationships together, an inverse line is drawn in the remaining quadrant. All points along this line deflect the remainder acreage from the opposite axis (fig. 4).

Final Model

Finally, a cost-plus-damage curve is added. We can trace various levels of expenditure counterclockwise through the diagram, use the functions in each quadrant as turning points, and sum the cost

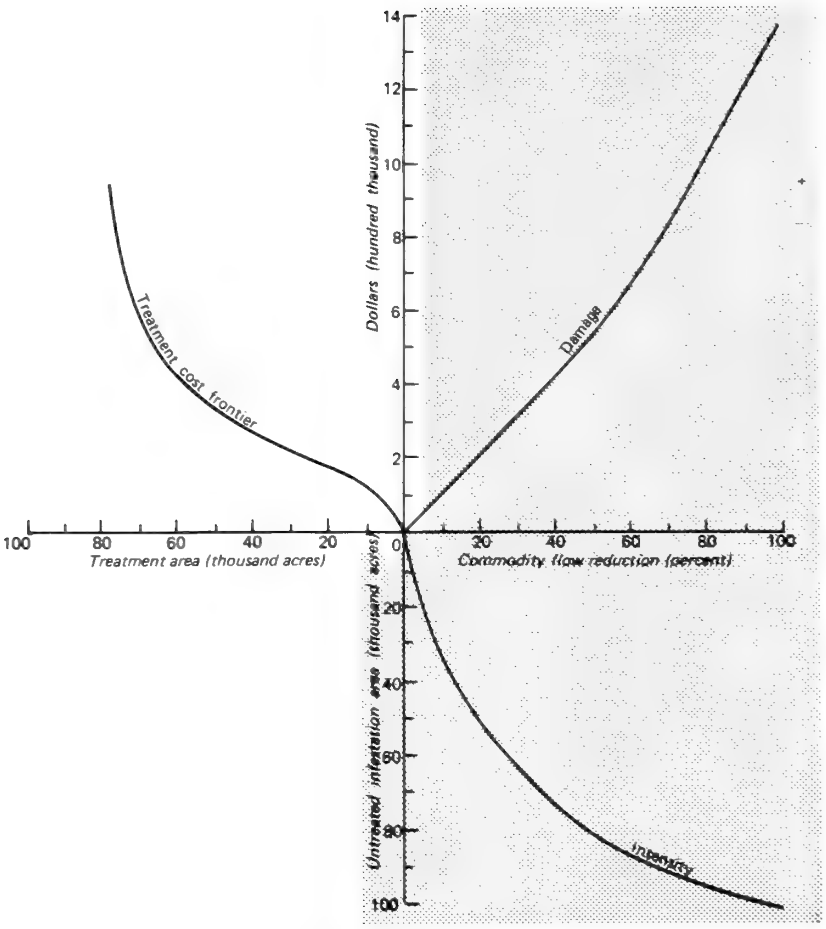

Figure 3.--Treatment-cost function--relationship between size of pest management project and program cost.

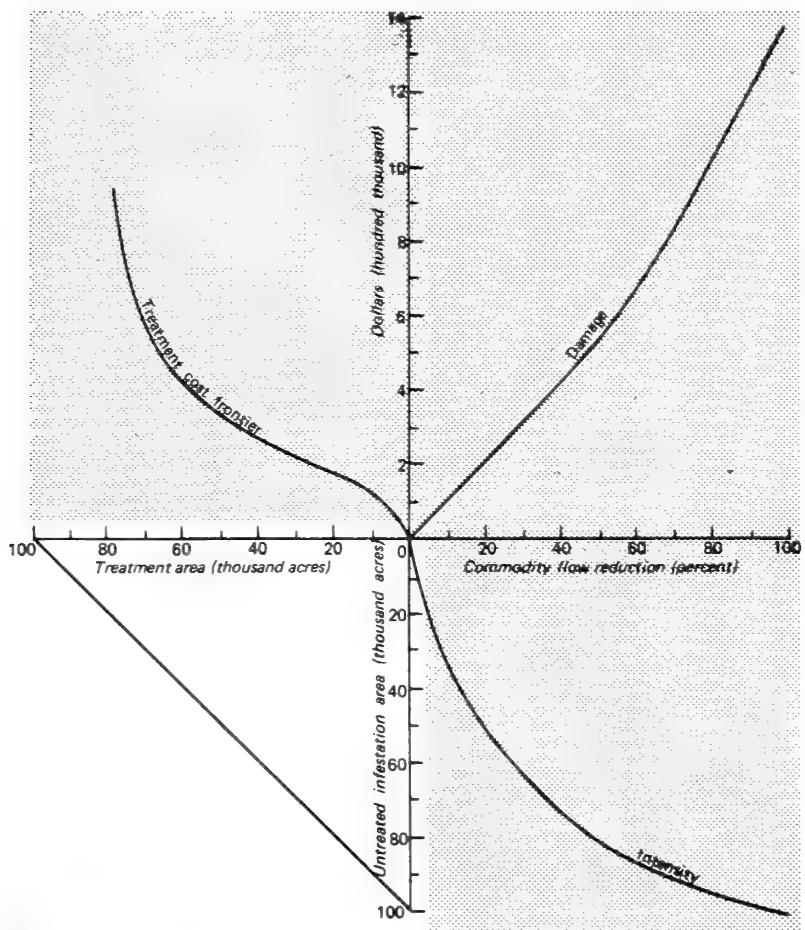

Figure 4.--Inverse line--deflection of remainder acreage from the opposite side.

and damage curves (fig. 5). Once the shape of the cost-plus-damage curve has been found, it is relatively simple to identify the low point and find the best size for treatment area and expenditure.

Tracing the point of least cost-plus-damage through the model for this planning unit indicates that optimum pest management and optimum product flow would be achieved by treating 51,000 acres of the 100,000-acre unit. At this level, the marginal damage equals the marginal pest management cost. That is, to spend beyond this level would add more to the cost than it would deduct from the damage.

A bonus feature of this model is its built-in priority for extending pest control to the kind and amount of forest land where treatment could do most to avert damage in the planning unit. The model was built on a hierarchy of potential value losses. Each value loss is associated with specific forest stand conditions that describe a damage susceptibility group. The sequence from least to greatest loss per unit area, as accumulated in the damage curve, corresponds with the cumulative acreage plotted on the lower axis. Therefore, acreage to be treated (or left untreated) can be specified by describing the stand conditions that identify the damage susceptibility groups in that particular acreage.

CONCLUDING REMARKS

The specific results are not especially important here. The framework is important--a way to link risk rating and forest protection prescriptions. The cost-plus-loss concept has been around for some time (Headley 1916, Sparhawk 1925), but it has never really been implemented in forest protection. Freeman et al. (1973) extended its use to define a pollution control model for the management of environmental quality. Now, with this further adaptation, we have a decision framework that merges damage susceptibility ratings and cost-plus-loss economic theory to pursue forest pest management action that is cost effective.

Techniques exist and are being validated for predicting forest stand losses from key characteristics of stand condition. By surveying the area distribution of these stand condition groups in a planning unit, the unit's potential damage can be forecast. This information is the basis for the intensity function that relates the potential infestation area and its likely impact on the level of product flow. The intensity function is the key to applying the economic theory because, acting as a production function, it links the cost and damage functions and trans-

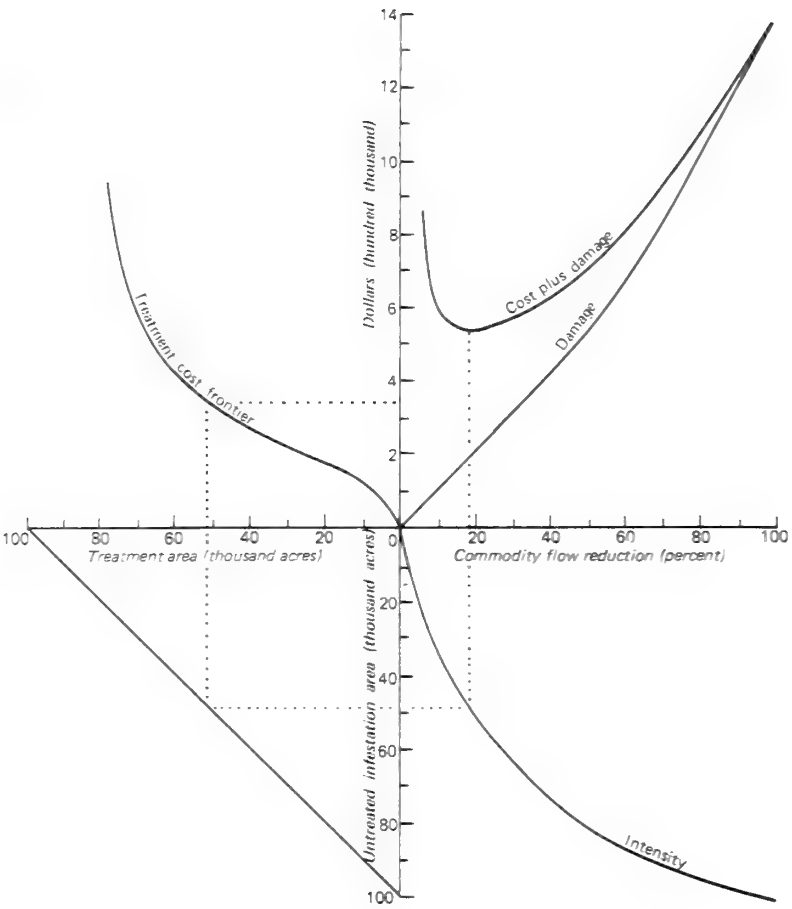

Figure 5.--Four-quadrant model of relationship among untreated infestation area, intensity, physical effects, dollar damages, size of treatment area, and costs.

lates pest management efforts (acres treated) to results measured as a reduction of impact. The combined model of cost, damage, and production functions provides management with a useful guide that uses least total cost as the criterion for investment decisions in forest protection efforts.

Finally, a word of caution is appropriate because values other than those for timber must be considered. Some areas may yield larger nonmarket values than others--recreational and wildlife values are prime examples. A simple economic analysis of timber values, such as illustrated, may underestimate the amount of protection that is appropriate for areas yielding amenity values. However, if information is given about the impact of infestation on forest amenities and nonfiber products, the model can be adjusted to incorporate these values as well. The decision framework compares increments of expenditure and focuses on relative effectiveness, so that the decisionmaker can see his alternatives in quantitative terms.

LITERATURE CITED

Campbell, R. W., and R. J. Sloan. 1977. Forest stand responses to defoliation by the gypsy moth. 34 p. For. Sci. Monogr. 19.

Freeman, A. M., III, R. H. Haveman, and A. V. Kneese. 1973. The economics of environmental policy. 184 p. John Wiley & Sons, Inc., New York.

Gansner, D. A., and O. W. Herrick. 1979. Forest stand losses to gypsy moth in the Poconos. 5 p. U.S. Dep. Agric. For. Serv., Res. Note NE-273. Northeast. For. Exp. Stn., Broomall, Pa.

Headley, R. 1916. Fire suppression, District 5. 57 p. U.S. Dep. Agric. For. Serv.

Herrick, O. W. 1981. Forest pest management economics--application to the gypsy moth, *Lymantria dispar* (L). For. Sci. [In press.]

Herrick, O. W., D. A. Gansner, and P. S. DeBald. 1979. Predicting stand losses from the gypsy moth: an application of automatic interaction detection. J. For. 77(2):91-94.

Sparhawk, W. N. 1925. The use of liability ratings in planning forest fire protection. J. Agric. Res. 30(8):693-762.

U.S. Forest Service. 1980. Integrated pest management. U.S. Dep. Agric., Program Aid 1251. Washington, D.C.

REVIEWER COMMENTS

Robert L. Talerico[1]

The keynote and overview speakers covered many of the problems associated with the development and implementation of hazard-rating systems. They provided the background for this symposium and touched upon many of the aspects that I feel must be addressed if we are to provide the forest manager with effective hazard-rating systems for forest insect problems.

The rating systems discussed have many common elements. They have identified variables that correlate hazard with measurements of factors such as tree age; basal area (growth rate, stand density); site (soil horizon depth, aspect, topographic position); history (damage, ground cover, defoliation); crown characteristics (tree growth form); and insect counts. These methods range from those already operational to those under development. Most of the operational systems are concerned with insects that kill trees outright (bark beetles, weevils, spittlebugs), while those systems concerned with defoliation (spruce budworm, gypsy moth) are still being developed or require refinement. The former might be a reflection of the economic consideration associated with the rapid mortality; the latter involves complex and subtle interactions associated with defoliation. These range from the scientific to the emotional and include perplexing political constraints.

The technology needed to provide the forest manager with solutions to the hazard-rating problem seems to be available. Most methods have evolved from regression techniques and include many sophisticated modifications of these techniques. However, some of the solutions presented here have shown that this degree of sophistication is not needed for all problems. As these methods reach the operational stage, data collection, analysis, and decisionmaking should be simplified so that only minimal computation is required by the user. Nearly all the methods discussed still require adequate validation and refinement before they can become useful tools for the manager.

Only one method has been devised to rate forest condition with respect to two insect pests. Where possible, hazard-rating problems should be combined to achieve savings in time and manpower. Likewise, the economic aspects of pest problems must be integrated into the rating method. Only one system addressed this consequence of insect damage. The forest manager needs decisionmaking criteria on which to base his decision and select the most appropriate course of action. Economic information is probably the most useful guide for the manager. He has little interest in the acres of defoliation, number of insects per tip, or active bark beetle spots. His prime concern is how many trees, cords, or board feet of timber he will lose. Specific dollar values can be determined for this kind of information.

We are all aware of the growing interest in technology transfer. Getting the research information to the user is an important aspect of the research process. The number of users that have attended this symposium is gratifying, but I note that researchers still outnumber users. This ratio must be reversed if we are to succeed in implementing these systems.

The organizers of this symposium have gathered a large array of people and methods concerned with hazard rating. Still, I am aware of several operational systems for the spruce budworm that are not represented here. I am sure there are other examples for other insects. Individuals or agencies who have developed and used these methods have done so to meet a pressing need for decisionmaking systems for their particular situation and forest type. In the future, information of this kind should be made available to the user community. Future methods should rely upon advanced remote sensing techniques to locate, identify, and initially categorize areas for pest management decisions.

Finally, I must agree with Chuck Olsen, who suggested that we define our terminology so that everyone know what we mean by hazard, risk, susceptibility, and vulnerability. In the spruce budworm literature, the latter two terms are defined in the mathematical sense of probabilities.

In summation, the symposium organizers have done a terrific job in putting together this program. The facilities are superb and a great deal of information has been communicated. The preceding should serve as a benchmark for future programs on hazard.

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